FINNISH NATIONAL DEFENCE UNIVERSITY

THE TECHNOLOGICAL MATURITY OF GROUND BASED DIRECTED ENERGY AIR DEFENCE SYSTEMS IN 2025-2030

Dissertation

Captain
Tuomas Pernu

GSOC 58

August 2017

FINNISH NATIONAL DEFENCE UNIVERSITY

Course **General Staff Officer Course 58**	Service Branch **Air Force**
Author **Captain Tuomas Pernu**	
Title **THE TECHNOLOGICAL MATURITY OF GROUND BASED DIRECTED ENERGY AIR DEFENCE SYSTEMS IN 2025-2030**	
Department Military Technology	Archived at FNDU Library
Date August 2017	Text pages 99 + 2 Appendices

ABSTRACT

Directed energy weapons (DEW) have been pursued by the military and defence industry since the 1980's. Some potential technology demonstrators have been showcased over the decades but not until recently there have been a number of promising programmes. This dissertation was performed to find out what is the applicability of DEWs in the Ground Based Air Defence (GBAD) domain in 2025-2030.

A thorough literature review was conducted to find answer to a sub-question: 'What are the DE technologies and systems under development for AA (Anti-Aircraft) and CRAM (Counter Rockets Artillery Mortar)?' It was established that there are 15 programmes in total of which 14 are laser and 1 is HPRF (High Power Radio Frequency) system.

Next a Delphi panel was used to find answers for the second sub-question: 'What is the maturity level of GBAD DEW in 2025-2030'. In total three Delphi iteration rounds were performed. This was followed by Technology Readiness Level (TRL) assessment done by utilizing USAF TRL calculator.

Finally the results of literature review, Delphi and TRL assessment were combined and it was established that there are three potential GBAD systems to reach full technological maturity in 2021-2029 which could mean the systems would be commonly in use in 2025-2035. Other main findings include:

- Despite the lengthy research and testing many obstacles remain to mature the technologies to the level where they could be deployed
- Output powers of current DEW are far from being adequate in engaging manned aircraft size targets
- DEWs can engage UAV's within 2-3km in 2021-2029
- DEWs can engage UAV's within 10 km in 2024-2030
- DEWs can engage manned aircraft and possibly ballistic missiles from ranges exceeding 10 km in 2026-2037

The main research question: 'What is the applicability of directed energy weapons when replacing or developing Finland's GBAD capabilities after 2025?' was answered by comparing the results with classified GBAD development plans. These results are presented in a separate classified annexe not part of this public document.

KEY WORDS Directed energy, Technological readiness, Ground Based Air Defence, Maturity assessment, Laser, HPRF, HPM

THE TECHNOLOGICAL MATURITY OF GROUND BASED DIRECTED ENERGY AIR DEFENCE SYSTEMS IN 2025-2030

Contents

1. INTRODUCTION ... 1
1.1. Project Aims and Research Questions ... 2
1.2. Limitations and Assumptions ... 3
1.3. Related Researches ... 4
2. RESEARCH METHODOLOGY ... 4
2.1. Futures Research Methods ... 4
2.2. The Applied Research Methodology ... 6
2.3. Delphi Method ... 8
2.4. Validating Delphi Results by Statistical Tests ... 10
2.5. Technology Readiness Level Assessment ... 12
2.6. Forecasting Years to Maturity based on TRL ... 15
3. LITERATURE REVIEW ... 17
3.1. Defining Directed Energy Weapons ... 17
3.2. Laser ... 19
3.2.1. Principles of Laser ... 20
3.2.2. Types of High Energy Lasers ... 23
3.2.3. Laser as an Air Defence Weapon ... 25
3.2.4. Laser Weapons under Development ... 27
3.3. High Power Radio Frequency Weapons ... 30
3.3.1. Principles of High Power Radio Frequency Weapons ... 30
3.3.2. HPRF Weapons under Development ... 33
3.4. Advantages and Disadvantages of DEW ... 34
3.4.1. Strengths of DEW ... 34
3.4.2. Weaknesses of DEW ... 35
3.5. Recent DEW Maturity Surveys ... 37
3.6. Conclusions of the Literature Review ... 41
4. APPLICATION OF RESEARCH METHODS ... 42
4.1. The Delphi Rounds ... 42
4.2. Round One of the Delphi Panel ... 46
4.2.1. Summary of Round One ... 53
4.3. Round Two of the Delphi Panel ... 53
4.3.1. Summary of Round Two ... 61
4.4. Round Three of the Delphi Panel ... 65
4.4.1. Summary of Round Three ... 71

4.5. Technology Readiness Level (TRL) Assessment of Current DEW Systems 72
4.5.1. Summary of TRL Assessment..74
5. RESULTS AND DISCUSSION 75
5.1. Findings of the Literature Review...75
5.2. Results of the Delphi Method...76
5.2.1. Results of Classic Forecast Delphi Questions...76
5.2.2. Results of Ranking Delphi Questions 79
5.2.3. Summary of Delphi Results 85
5.3. Results of TRL Assessment 86
5.4. Discussion of the Results 89
5.5. Answers to Research Questions 93
5.5.1. What are the Technologies and Systems under Development for AA and CRAM? 93
5.5.2. What is the Maturity Level of GBAD DEW in 2025-2030?..94
5.5.3. What is the Applicability of DEW when Replacing or Developing Finland’s GBAD Capabilities after 2025?...95
5.6. Limitations to Findings 96
6. CONCLUSIONS AND RECOMMENDATIONS...97
6.1. Research Aims...97
6.2. Summary of the Research 97
6.3. Literature Review..97
6.4. Delphi Method...98
6.5. TRL Assessment 98
6.6. Recommendations for Further Work..99
6.7. Concluding Statement 99
7. REFERENCES..100
8. APPENDICES...109
8.1. Inserted Values and Results of TRL Calculator...109

List of Figures

Figure 1: Roadmap for Answering the Research Questions 7
Figure 2: Sub-systems with Different TRL's 14
Figure 3: Aircraft Technology Readiness Level Timeline 16
Figure 4: Forecasted UGV Technology Readiness Level Timeline 16
Figure 5: The Electromagnetic Spectrum 18
Figure 6: Laser Light Amplification 21
Figure 7: Principle of Laser Oscillator 21
Figure 8: Principle of Master Oscillator Power Amplifier 22
Figure 9: Principles of Front-door and Back-door coupling 32
Figure 10: SWaP Progression Plans of US Missile Defence Agency 36
Figure 11: Results of Defence IQ Survey Question 1 38
Figure 12: Results of Defence IQ Survey Question 2 39
Figure 13: Answer Distribution of CNAS Poll DEW Question 1 39
Figure 14: Answer Distribution of CNAS Poll DEW Question 2 40
Figure 15: User View of FacilitatePro 44
Figure 16: Design Process of Delphi Rounds in this Research 44
Figure 17: Round 1 Q1 Answers 48
Figure 18: Round 1 Q3 Answers 49
Figure 19: Round 1 Q4 Answers 50
Figure 20: Round 1 Q6 Answers 51
Figure 21: Round 2 Q3 Answers 56
Figure 22: Round 2 Q4 Answers 57
Figure 23: Round 2 Q7 Answers 59
Figure 24: Round 2 Q8 Answers 59
Figure 25: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when laser weapons will be commonly used by the military?* 62
Figure 26: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when land based laser weapons are mature enough to be used for air defence?* 63
Figure 27: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when HPRF weapons will be used by the military?* 63
Figure 28: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when land based HPRF weapons are mature enough to be used for air defence?'* 64
Figure 29: Round 3 Q2 Answers 68
Figure 30: Round 3 Q3 Answers 68
Figure 31: Round 3 Q6 Answers 70
Figure 32: Round 3 Q7 Answers 70
Figure 33: Baseline values for USAF TRL Calculator 72
Figure 34: Summary View of USAF TRL Calculator 73
Figure 35: Example of Data View of USAF TRL Calculator 73
Figure 36: The Development of Answers to: "*Year when laser weapons will be commonly used by the military?"* 77
Figure 37: The Development of Answers to: "*Year when land based laser weapons are mature enough to be used for air defence?"* 78
Figure 38: The Development of Answers to: "*Year when HPRF weapons are commonly used by the military?"* 78
Figure 39: The Development of Answers to: "*Year when land based HPRF weapons are mature enough to be used for air defence?"* 79
Figure 40: DEW Programmes' TRLs and Current Target Sizes 86
Figure 41: DEW Programmes' TRLs and Aspired Target Sizes 87

List of Tables

Table 1: Chi-Square Distribution table 12
Table 2: Technology Readiness Levels of US DoD 13
Table 3: Power Requirements for Different Target Types....26
Table 4: Laser Weapon Programmes 29
Table 5: HPRF Weapon Programmes....33
Table 6: Demographics of the Delphi Panel 43
Table 7: Round One Questions and Remarks 46
Table 8: Round 1 Q2 Answers....48
Table 9: Round 1 Q2 Answers Clustered....49
Table 10: Round 1 Q5 Answers....50
Table 11: Round 1 Q5 Answers Clustered....51
Table 12: Round 1 Q7 Answers....52
Table 13: Round 1 Q7 Answers Clustered....52
Table 14: Round 2 Questions....54
Table 15: Round 2 Q1 Answers....55
Table 16: Round 2 Q2 Answers....55
Table 17: Ranking based on Round 2 Q2 Answers 56
Table 18: Round 2 Q5 Answers....57
Table 19: Ranking based on Round 2 Q5 Answers 58
Table 20: Round 2 Q6 Answers....58
Table 21: Ranking based on Round 2 Q6 Answers 59
Table 22: Round 2 Q9 Answers....60
Table 23: Ranking based on Round 2 Q9 Answers 61
Table 24: Round 3 Questions....65
Table 25: Round 3 Q1 Answers....67
Table 26: Round 3 Q4 Answers....69
Table 27: Round 3 Q5 Answers....69
Table 28: Round 2 Q8 Answers....71
Table 29: TRL Assessment of DEW Programmes 74
Table 30: Final Answers to: *'Rank the following factors advancing laser weapon maturity in order of significance'* 80
Table 31: Final Answers to: *'Rank the following factors hindering laser weapon maturity in order of significance'* 80
Table 32: Final Answers to: *'Rank the following factors advancing HPRF weapon maturity in order of significance'.* 82
Table 33: Final Answers to: *'Rank the following factors hindering HPRF weapon maturity in order of significance'* 83
Table 34: Final Answers to: *'Rank the following non-technical factors that influence/could have an impact on the proliferation of DEW in order of significance'*....84
Table 35: Main Findings Combined 90
Table 36: Ongoing Programmes Pursuing AA/CRAM Capability....94
Table 37: Maturity of GBAD DEW in 2025-2030 95

List of Abbreviations

AA	Anti-Aircraft
ABL	Airborne Laser
ATL	Advanced Tactical Laser
CRAM	Counter Rockets Artillery Mortar
DE	Directed Energy
DEW	Directed Energy Weapon
DPAL	Diode Pumped Alkali Laser
EMP	Electromagnetic Pulse
FDF	Finnish Defence Forces
FEL	Free Electron Laser
GBAD	Ground Based Air Defence
GBAD DE OTM	Ground Based Air Defence Directed Energy On The Move
HEL	High Energy Laser
HEL MD	High Energy Laser Mobile Demonstrator
HELE/LWM	High Energy Laser Effector/Laser Weapon Module
HELLADS	High Energy Liquid Laser Air Defense System
HPEW	High Power Electromagnetic Weapon
HPM	High Power Microwave
HPRF	High Power Radio Frequency
IED	Improvised Explosive Device
J	Joule
JHPSSL	Joint High Power Solid state Laser
JP	Joint Publication
kW	kilo Watt
LAWS	LAser Weapon System
LDEW	Laser Directed Energy Weapon
MLD	Maritime Laser Demonstrator
MOPA	Master Oscillator Power Amplifier
MW	Mega Watt
NASA	National Aeronautics and Space Administration
RELI	Robust Electric Laser Initiative
RF	Radio Frequency
SME	Subject Matter Expert
SQ	Sub-Question

SSL	Solid State Laser
SWaP	Size Weight and Power
TLS	Tactical Laser System
TRL	Technology Readiness Level
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
UK MOD	UK Ministry of Defence
US DoD	US Department of Defense
USAF	United States Air Force

THE TECHNOLOGICAL MATURITY OF GROUND-BASED DIRECTED ENERGY AIR DEFENCE SYSTEMS IN 2025-2030

1. INTRODUCTION

"You miss hundred percent of the shots you don't take."

Wayne Gretzky (1960-)

In contrast to many business domains where achieving second and third place still means making a profit, on the battlefield, there are no in-betweens, you are either the first or you are the last. Throughout the history, technological advances have been shaping the battlefield, and in many occasions, the one with the technical advantage has triumphed. This has resulted in a willingness to invest more and more in sophisticated military equipment, and thus a technology race has been part of military ever since the era of crossbows and catapults.

In general, defence acquisitions are based on capability needs stemming from the capability owner's analysis regarding the battlefield of the future. Although the future battlefield analysis is a complicated and time-consuming process considering numerous facts and figures, the cause for a capability need can be categorised into two main classes. The other is the need for an entirely novel capability and the second is the need to renew or modernise the existing capability. In many cases, the capability requirement is related to the technological changes in the battlefield.

Regardless of the cause, a thorough preliminary assessment of the availability, usability, and affordability is conducted at the very beginning of the acquisition process. Many aspects of the technological and tactical development are constantly followed, but in most cases, a separate and distinct study is in place. The preliminary assessment provides, should it be conducted and appropriately resourced, the basics to assess the feasibility of the programme to proceed to further stages. In some cases, the technology aspired is not mature enough, and sometimes there may be affordability or availability issues. Nonetheless, these all can be regarded as showstoppers or at least they are factors that must be known once the decision is made for the continuation of the acquisition programme.

Should an acquisition programme fail to deliver there normally are only two poor options left. We either accept we did not get the pursued capability or we invest more in the programme thus spending money originally allotted to something else. In both cases, the results will be severe and may even lead to lost battles and even wars. Hence, reliable and justifiable methods undertaken meticulously are or at least should be, an inherent part of defence acquisition and procurement. As the defence budgets are finite, no nation just cannot afford careless acquisitions as they will incur capability related knock-on effects for many decades to come. The precise and accurate processes decrease the chance of procuring capability with an unfavourable value for money ratio and, in the worst case, acquiring materiel not fit for purpose.

1.1. Project Aims and Research Questions

This dissertation intends to provide support for the decision makers of the future Ground Based Air Defence (GBAD) acquisitions. It is a research assessing specifically the maturity of Directed Energy Weapon (DEW) technologies and their feasibility as part of Finland's GBAD arsenal in the decades to come. The intention is not to find justifications why DEW's should or should not be acquired or to compare modern contemporary weapons with DEWs. These are, however, paramount questions and it is assumed they will be researched and studied as the programme proceeds to following phases. The research questions for this study are introduced and covered in detail later in this sub-chapter.

For decades The DEWs have been seen as the future technology revolutionising military. Should they live up to their promises the military could see game-changing effects in numerous different areas, not least in GBAD. Thus far, however, DEWs have not been able to meet the expectations and promises, but there are clear signals that things may be changing. Recently we have witnessed several live demonstrators in action, mainly lasers, with promising results. Furthermore, there have been prominent announcements by major US and British defence actors stressing the importance of funding and further developing DEWs. The big question is how to forecast what will happen in the DEW scene and when?

As it was said, this project seeks to find scientifically justified facts to enhance decision makers' chance to make timely and accurate decisions regarding GBAD acquisitions concerning the decades to come. The maturity of any technology is vital information when decisions are made regarding capability gaps. The decision makers should be, earlier the better, informed of any possible technological foxholes regarding the sought capability. This will enable timely decisions to allocate resources.

This research is not part of a particular acquisition programme thus it provides a more of an overview of the maturity of DEW technology instead of focusing on a specific domain of GBAD. The focus is on assessing the maturity of mobile land-based Anti-aircraft (AA) and Counter Mortar Artillery Rockets (CRAM) systems in 2030 and beyond. Seaborne and airborne applications are, however, not excluded. This is because some of the main achievements in the field of DEW are related to maritime and airborne applications.

Since this study is generic in nature, it does not adopt a single definition or requirement for a feasible GBAD solution as there are numerous different user needs. A system capable of repelling small unmanned air vehicles (UAV), which is one GBAD task, will not necessarily be feasible to prosecute incoming ballistic missiles. This a classic requirement writing problem; one must understand the user needs first. Hence this study looks at the GBAD domain, together with its target portfolio, as a whole.

The research intends to answer the following main research question:

- What is the applicability of directed energy weapons when replacing or developing Finland's GBAD capabilities after 2025?

The main question is supported by the following two sub-questions (SQ):

1. What are the DE technologies and systems under development for AA and CRAM? (SQ1)

2. What is the maturity level of GBAD DEW in 2025-2030? (SQ2)

However, albeit this research has a particular main research question, it does not mean that answers to the sub-questions would not serve a purpose by themselves. On the contrary, their answers can be used in their right for other uses too. For example, should the need be, the main research question could be tailored to provide answers to suit another nation while utilising the answers of SQ 1 and 2.

1.2. Limitations and Assumptions

There are challenges in writing an unclassified research of a current or future military topic. Many areas of this research are closely related to classified information. This is especially the case when dealing with novel technology. It would be extremely time consuming and somewhat impossible to gather enough classified material to conduct a thorough scientific thesis of a delicate subject like this. That would require initiating an official acquisition programme with all the resources behind it.

Moreover, there are also classification issues in applying the results of this study to Finnish national defence development programmes. Hence all conclusions relating to national defence are covered in a separate classified annexe which will not be presented in the unclassified section of this study. Also, as this thesis has a steadfast deadline and is conducted as part of an academic degree there are limitations regarding the available time and manning.

1.3. Related Researches

This research is a part of Army Command’s programme for replacing and enhancing Ground Based Air Defence capabilities and bases its threat scenario to a future air threat study. Also, it utilises and supports the following FDF’s research programme areas: surveillance of air vehicles, air defence in nation’s defence, countering air threat of the future and missile threat management. The specific topics and connections to the related researches are covered in the classified annexe which is not publicly available.

2. RESEARCH METHODOLOGY

To answer the research questions, there was a need to decide which methods could be implemented together with understanding the possible interrelations of the questions. First, the research questions were analysed to enable focusing on the right field of research methods. An important notion concerns the time dimensions of the research questions. SQ2 clearly concerns matters of the future whereas SQ1 is to do with the ‘as is’. As a result, a need for multiple approaches was identified. To provide answers for SQ2, there was a need for a technology oriented futures research methodology. SQ1, on the other hand, could be replied to by performing a literature review of the DEW technology and the current situation of the systems.

The main research question, on the other hand, called for comprising the answers of SQ1 and 2 together with the plans how Finnish Air Defence will meet the requirements of the future battlefield.

Based on the notion that SQ1 required a futures research method, a number of them were assessed and to enable the selection of the most useful one. This process is further described in the following chapter.

2.1.Futures Research Methods

There are various futures research methods utilised on a broad scope of research topics across the academic and business domains. For this research, there was a need for a method/s that would provide valid answers in assessing the technological maturity of DEWs in the years to come.

As the assessment of technical maturity has been an important part of both business and military for many decades, some methods have been developed. As a significant feature, many of these methods have been utilised in numerous researches and studies, and thus their applicability and validity can be assessed based on their actual real world results. A characteristic of futures research is that one can evaluate how good the results were after the forecasted date has become a reality. The downside is, however, that many of these studies are classified, and hence their validity or accuracy cannot be assessed. Regardless of the classification issues, a great number of unclassified academic papers can be found which not only implement the methods but also evaluate their suitability [49][63]. The assessment of the validity of a particular method in the context of this study was performed by searching both studies that implemented futures research methods as well as literature on futures research.

A comprehensive and somewhat exhaustive list of futures research methods is portrayed in Futures Research Methodology 3.0 edited by J.C. Glenn and T.J. Gordon [30]. Futures research methods are commonly divided into two categories; normative and exploratory [68] [55]. These types differ mainly in their approach to the future. In normative approach one first establishes future goals, desires, needs or missions. The path to achieve, or avoid; these targets are then studied. Exploratory methods, on the other hand, are more classical methods of actually forecasting the future. They, as the name suggests, explore possible futures and assess their probabilities. Exploratory methods mainly analyse historical data and forecast by following trends and patterns [68].

There are, however, occasions when both exploratory and normative methods are employed in conjunction, and there also are methods which incorporate attributes from both categories. Furthermore, views are dating back to 1960s, which support the combined use to achieve validity [55]. This aggregation of normative and explorative approaches has already partially occurred, and there are supporters for a more holistic approach to futures research instead of relying on a single method [4]. This trend can also be seen in many studies where both normative and explorative methods are applied.

A conclusion can be drawn that despite the number of methods, a single method seldom provides a justified and valid answer. In fact, many of them seem more or less artificial when it comes to actual differences [30]. This may result in a complicated situation when the researcher is assessing which method would best serve his/her quest in answering the research questions.

As per this research, some of the methods could be quickly ruled out as they are not designed to provide answers to technological problems. As examples of the futures research methods that were considered invalid for this research from the outset are ‘Multiple Perspective Concepts’, ‘Morphological Analysis’ and ‘Heuristics Modelling’.

It needs to be appreciated that the very nature of futures research is heavily dependent on the situation when the research is conducted. Numerous variables may, and likely will change over the course of years and thus the results are no longer correct. As Roy Amara [4] puts it; the future is not predetermined, and it can be changed by our choices and decisions. This fact about the essence of future should be kept in mind when reading the results of this study. The results reflect only to the knowledge at hand when the study is conducted; any change can either hinder or accelerate the development and proliferation of DEW. This study provides information for decisions made in 2017-18. For later use, the background situation has to be checked to identify possible changes and analysis made whether the results are still valid. Pivotal background information includes, but is not limited to, threat, funding, legislature, and unprecedented technological breakthroughs. These are all attributes which may mould the future of DEW. For example, a new threat which is seen only to be repelled by using DEW would increase the funding and thus enhance the development resources which could result in a drastic change in the maturity forecast. On the other hand, should we see the DEWs, laser, in particular, clash with the rules of war, for instance, we could witness an entirely opposite situation.

2.2. The Applied Research Methodology

In order to answer the main research question we first have to answer the sub-questions. Furthermore, it is evident we must have answers to SQ1 prior to tackling SQ2. One simply requires adequate understanding of the problem space, the DEW technology in this case, before the implementation of the methods of SQ2 is possible.

To allow us the use of appropriate and suitable research methods to tackle all the questions an analysis was performed. Based on the analysis a set of methods were selected. The methods alongside with the answering logic are depicted in Figure 1.

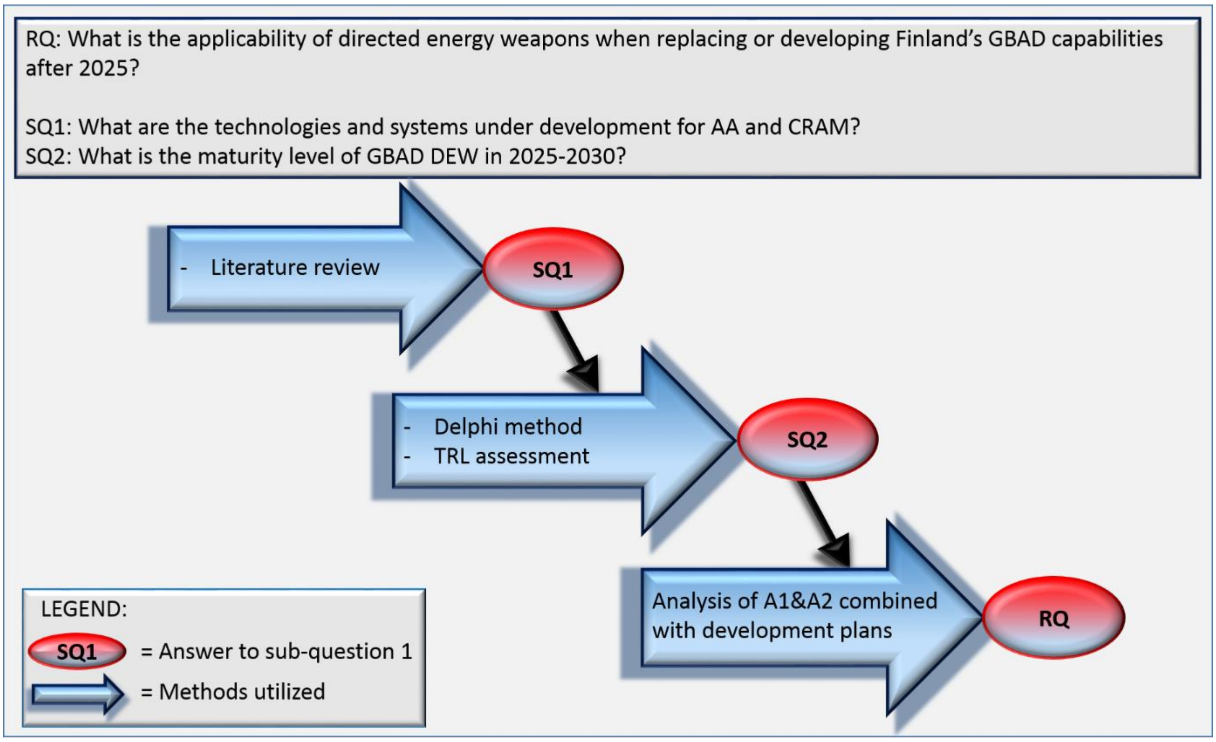


Figure 1: Roadmap for Answering the Research Questions.

It was decided that literature review amended with possible expert interviews would provide answers for SQ1. There are problems relating to only using open and unclassified sources, and this needs to be taken into account when reading the results. In other words, there may be technological advances and capabilities which are not presented here. Nonetheless, the majority of the basics will remain unchanged and mitigate invalid/missing information the literature review pursues to cover the topic as exhaustive as possible. As this is a basic research regarding the maturity of DEW technology, there is no need at this point to describe detailed information of a particular weapon system. Furthermore, no attempt is made in comparing the current systems' capabilities against each other. Should the need be, this will be performed during the acquisition programme using the information provided by the tenders.

Based on the search of possible research methods the primary method for answering SQ2 was decided to be the Delphi- method. As shown in Figure 1, one of the main purpose of the answers of SQ1 is to enable the research to continue to SQ2. Without the insight and understanding achieved in answering SQ1 there would be little chance of composing well-founded questions for the Delphi panellists to answer.

As was discussed earlier, an implementation of a supporting method is highly recommended as the additional method would enhance the validity of the results. The use of complementary methods is recommended by many practitioners of futures research as a single method rarely provides sound and justified answers. Hence it was decided to seek answers to SQ2 also by using a method called TRL assessment.

While the results provided by TRL assessment would serve as a complimentary data but they could also be used should we fail to get results from the Delphi. After all, as this is research with a firm deadline it was also seen vital to mitigate the possible risk of either not being able to form a credible Delphi panel or in the event of unacceptable dropout rate of panellists. This mitigation was done by including the TRL Assessment method.

The selected methods are introduced in detail in the following chapters.

2.3. Delphi Method

A method applied in a high number of futures technological maturity studies is the Delphi method. It is a method developed by the RAND- Corporation in the 1950s to provide a systematic approach to utilise expert opinions [16][34]. The early pioneers, if not developers, were Norman Dalkey and Olaf Helmer who introduced iteration into the process after which it received the name Delphi [16]. According to Helmer, the very foundation of the Delphi was the realisation that projections of the future were mostly based on the personal expectations of individuals rather than on predictions derived from a well-established theory [34].

From this standpoint, the Delphi was developed to aggregate the judgements of subject matter experts while minimising interference and maximising validity. As the notion of personal expectations suggest, there is a scientific problem when dealing with expert opinion. Dalkey sums up the difference between knowledge, opinion and speculation by saying there is a distinction in the likelihood of correctness. In knowledge, the likelihood is high, in speculation low and opinion something in between [15]. The problem being there is no valid method to measure the degree of likelihood, hence, in the eyes of science, opinion has little weight. Nonetheless, it is the opinions that should be aggregated since the question is concerning the future which hardly anyone can possess knowledge of.

Furthermore, as stated by both Dalkey and Helmer, there is solid evidence that opinion may be interfered when shared in face-to-face conversations. This occurs because of the presence of dominant individuals, authority issues, bandwagoning, unwillingness to abandon publicly expressed opinions and group pressure [34][15]. These all alter the result and have led to inclusion of anonymity as one of the three cornerstones of Delphi. It is important that the group members are kept anonymous to one another to enable the experts to maintain their opinions and change them only when they see it necessary. The anonymity, however, does not mean the researcher would not be aware of the answers' identity. The repliers' identities are in some cases crucial information when the answers are analysed.

The second main character is the iteration with controlled feedback [15]. The iteration process performs the interaction among the panellists. Iteration is usually done by introducing the summary of the results of the previous stage for the panellists before they are to answer the next round. With the information at their use, they are then asked to reassess their previous answers. They are not necessarily expected to arrive at the same conclusion even after multiple iteration rounds, but their responses typically tend to converge. It is, in fact, important to understand the result is not supposed to be unanimous. After the iteration rounds, the researcher then implements statistical analysis to establish the result of the group response. The result of the group response reflects the opinion of all the experts. This is based on the statistical method the final answer is derived with. It is widely stated in the literature that median provides the most accurate results when a classic forecast Delphi is conducted [15][34][16]. In a ranking –type Delphi, however, Kendall's W is the most commonly utilised statistical method in assessing group consensus [58].

The Delphi technique in its simplest form eliminates committee activity among the experts altogether and replaces it with a carefully designed program of subsequent interrogations interspersed with information and opinion feedback [34].

2.4. Validating Delphi Results by Statistical Tests

Interpreting the Delphi results depends on the type of Delphi implemented. Ranking type Delphi requires statistical methods to ascertain the validity and level of consensus whereas in classic Delphi a more direct approach can be utilised. The vitality of implementing statistical tests to ensure the results are statistically valid is commonly stressed by the researchers [10][35][49][58]. Furthermore, without such testing, it would be difficult to establish stopping criteria for iteration.

Also, the statistical approach provides rigour and reliable statistics especially when the sample size is small as it enables us to determine the degree of consensus among the respondents [10]. It is also important to utilise an accepted statistical method instead of relying on percentages or standard deviation as they do not ensure a consensus has been reached [10]. The latter applies specifically to ranking type Delphi.

Based on those above, a method to assess the group's overall agreement was required for this study too.   This method should be applicable in a situation where multiple factors are rated by multiple respondents and specifically to ascertain that the panel had in fact reached consensus. Based on recommendations made by Delphi practitioners and statistics professionals the Kendall coefficient of concordance (W) was selected as the statistical method to assess the group consensus of the ranking questions [37][49][62][35][10][83]. Furthermore, the statistical significance of the results was decided to be assessed by computing the p-value[62].

The Kendall coefficient of concordance (W) measures the degree of association among several sets of rankings. It can be used to reject the null hypothesis which in this case assumes that there is no significant agreement among the panellists. To compute W, we begin by arranging the data into a $k \times N$ table where each row indicates the ranking of factors by a single panellist. In the table, we have k number of panellists and N number of ranked attributes. Then the average rank $\bar{R}_i$ is established by dividing the sum of the ranks in a column by k. After this we calculate the grand mean of $\bar{R}_i$'s by dividing their sum by k [37][62].

To compute Kendall coefficient of concordance we use equation: $W = \frac{\sum_{i=1}^{N}(\bar{R}_i - \bar{R})^2}{N(N^2-1)/12}$

In the equation:

N = number of ranked objects

$\bar{R}_i$ = average of the ranks assigned to the ith object

$\bar{R}$ = grand mean of the ranks assigned across all objects

$N(N^2-1)/12$ = maximum possible sum of the squared deviations, i.e. the numerator which would occur if there were perfect agreement among the k rankings

Kendall's W gives a value ranging from zero to one. Zero means the panellists are in total disagreement whereas one refers to perfect concordance [62]. While there are no universal and absolute threshold values for assessing the level of agreement some commonly used limits can be found. Based on Schmidt [58] and Okoli et.al. [49], this thesis uses 0.7 as a level for strong agreement and 0.5 for moderate agreement. These limits are not, however, considered absolute and thus the analysis may conclude that a strong agreement has been reached with W values less than 0.7.

It needs to be emphasised, however, that a significant value of W does not indicate correct answers. It merely states the respondents are in consensus. It is the Delphi iteration which, if the panellists are chosen correctly, legitimises the accuracy of the answers.

Whereas W informs us about the agreement of the panellist, it does not provide information about statistical validity. This means we do not know if the results are based on chance. Hence there is a need to test the significance of the particular W. This is done by computing the p-value using MS Excel's CHIDIST- function. However, before CHIDIST- function can be used we need to compute Chi-Square (X^2) distribution value.

The X^2 distribution value is calculated by using the equation: $\mathrm{X}^2 = k(N-1)W$

In the equation:

k = number of panellists

N = number of ranked objects

W = Kendall coefficient of concordance

The MS Excel's CHIDIST- function calculates the right-tailed probability of the Chi-Square distribution and provides an accurate *p*- value. To provide an idea how the statistical validity could be obtained without MS Excel a short introduction is presented next together with a version of the Chi-Square distribution table (Table 1) [62].

After computing the X^2, the value is compared with the critical values of the chi-square distribution depicted in table 1 below. The correct value for 'Degrees of Freedom' *(Df)* is N-1, i.e. if N is 10 then $N-1 = 9$ so Df is 9. The W value is deemed statistically significant if the X^2 value exceeds the value of the decided column. The column is chosen based on the accepted risk level which most commonly is either 0.05 or 0.01 [62]. In this thesis, we consider 0.05 as the threshold value and as said we let MS Excel compute the *p*-value directly, so there is no need to refer to the table.

	Chi-Square (χ^2) Distribution									
	Area to the Right of Critical Value									
Degrees of Freedom	0.995	0.99	0.975	0.95	0.90	0.10	0.05	0.025	0.01	0.005
1	—	—	0.001	0.004	0.016	2.706	3.841	5.024	6.635	7.879
2	0.010	0.020	0.051	0.103	0.211	4.605	5.991	7.378	9.210	10.597
3	0.072	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.345	12.838
4	0.207	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277	14.860
5	0.412	0.554	0.831	1.145	1.610	9.236	11.071	12.833	15.086	16.750
6	0.676	0.872	1.237	1.635	2.204	10.645	12.592	14.449	16.812	18.548
7	0.989	1.239	1.690	2.167	2.833	12.017	14.067	16.013	18.475	20.278
8	1.344	1.646	2.180	2.733	3.490	13.362	15.507	17.535	20.090	21.955
9	1.735	2.088	2.700	3.325	4.168	14.684	16.919	19.023	21.666	23.589
10	2.156	2.558	3.247	3.940	4.865	15.987	18.307	20.483	23.209	25.188
11	2.603	3.053	3.816	4.575	5.578	17.275	19.675	21.920	24.725	26.757
12	3.074	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217	28.299
13	3.565	4.107	5.009	5.892	7.042	19.812	22.362	24.736	27.688	29.819
14	4.075	4.660	5.629	6.571	7.790	21.064	23.685	26.119	29.141	31.319
15	4.601	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.578	32.801
16	5.142	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32.000	34.267
17	5.697	6.408	7.564	8.672	10.085	24.769	27.587	30.191	33.409	35.718
18	6.265	7.015	8.231	9.390	10.865	25.989	28.869	31.526	34.805	37.156
19	6.844	7.633	8.907	10.117	11.651	27.204	30.144	32.852	36.191	38.582
20	7.434	8.260	9.591	10.851	12.443	28.412	31.410	34.170	37.566	39.997

Table 1: Chi-Square Distribution table. Adapted from [66].

2.5. Technology Readiness Level Assessment

The concept of Technology Readiness Levels (TRL) and their assessment was first introduced by NASA in 1974 [9]. The first scale had seven levels, but it has evolved over the years to its current form of encompassing nine tiers. TRL assessment was rapidly adopted by many militaries and other governmental organisations. Amongst the actors utilising the TRL concept, there are NASA, European Space Agency, UK Ministry of Defence, US Department of Defense and US Department of Energy [22][71][74][76]. The list is by no means exhaustive but provides an idea how pervasive the TRL concept is.

The idea behind TRL's is a commonly understood method for explaining to collaborators and stakeholders the maturity of a particular technology [9]. In other words, TRL's provides a common language and rigour for assessing and discussing an extremely complicated issue without interpretation problems or vested interests. The table below depicts the nine levels and their descriptions as defined by US DoD.

Technology Readiness Level		Description
1.	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2.	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3.	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4.	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5.	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components.
6.	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7.	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8.	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9.	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Table 2: Technology Readiness Levels of US DoD. Adapted from [73].

It is noteworthy that technological readiness of a system is an aggregate of the TRL's of its sub-systems [71]. Normally, at any given time during the systems development, the individual sub-systems' technological readiness levels vary from one another. This is because each sub-system is developed individually and its maturing does not depend on other sub-systems. As a consequence, there may be a situation where individual sub-systems are on TRL8 while some are on TRL4. It follows that the TRL of parent system cannot be higher than any of its subordinate systems [71]. This idea is illustrated in Figure 2 which depicts a generic TRL assessment of a missile system. In addition, one must also bear in mind that even if the example missile system reaches TRL9, it needs to be integrated into a platform and also requires systems for loading, maintenance and logistics. These systems may not yet have reached TRL9, so the capability will not be in use although the missile system has reached full maturity.

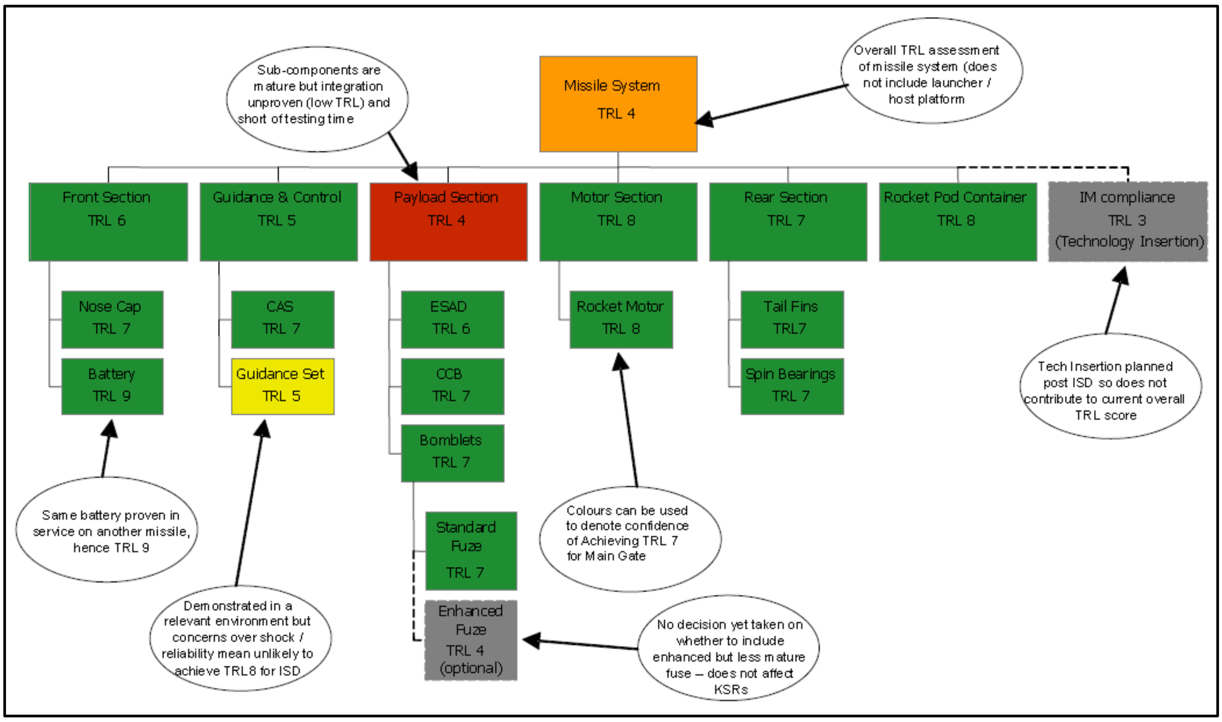


Figure 2: Sub-systems with Different TRL's [71].

Many of the organisations utilising TRL's have tailored NASA's scale and its definitions, but the main idea is the same. As this research concerns military applications, it is seen justifiable to implement a bespoke military scale. In addition to selecting the scale to be used, there was also a need for a calculator to assist with the assessment. It was found that there are both USAF [45][78] and UK MOD TRL [70] calculators available online. The UK MOD version is, in fact, a system readiness tool and thus takes a more holistic view. Nonetheless, both calculators are applicable for this research.

In this research, it was decided to use the USAF version. This decision stems from the limited access to data, as this is an unclassified research, combined with the massive amount of metrics the UK MOD calculator requires. The assessment was that there just was not enough accessible data that could have enabled the use of the UK MOD calculator. This does not, however, mean that we have access to all the metrics for the USAF calculator either, but the number of assumptions is significantly smaller. The use and the deficiencies of the selected TRL calculator are discussed in chapter 4.5.

2.6. Forecasting Years to Maturity based on TRL

This research finds TRL assessment useful as it provides a justified and proven method for assessing current maturity of DEW. Furthermore, after assessing TRL's of the DEW systems, we have a baseline for determining the timeframe when they could reach full maturity (TRL9). This assessment can then be compared with the results of Delphi panel for further analysis and discussion.

For us to estimate the time required for a system to obtain TRL 9, we can use two methods. We can utilise historical data of past TRL development, or we can draw conclusions from other studies which have assessed TRL progression.

Examples and graphs of historical data can be found in the literature, and they exhibit examples of both slow and fast maturing. As an example of rapid maturing is the noise-reducing chevrons for which it took only a total of seven years from TRL 1 to TRL9 [9]. The chevron case is described as exceptional, and it also needs to be appreciated that it does not consist finesse electronics or mechanics as it is a new design of a jet engine's nozzle.

A study which has composed a table indicating TRL maturation timeline states that the maturing from TRL1 to TRL9 ranges from 4 to 22 years [44]. The aircraft industry related table, found in Figure 3, shows there are significant differences in the timeline depending on the technological complicatedness of the system. In other words, the more simple systems without airworthiness testing mature in less time than the complicated onboard systems. When the simplest systems (ground-based flight control) are excluded, we can see the years to maturity is between 17-22 years. Moreover, the graph indicates the maturing occurs more or less intermittently. All programmes contain stages of both slow and rapid maturing, and these stages occur in different phases of the development curve. To sum up, the table needs to be interpreted with caution, but it can assist in drawing conclusions regarding the timeframe.

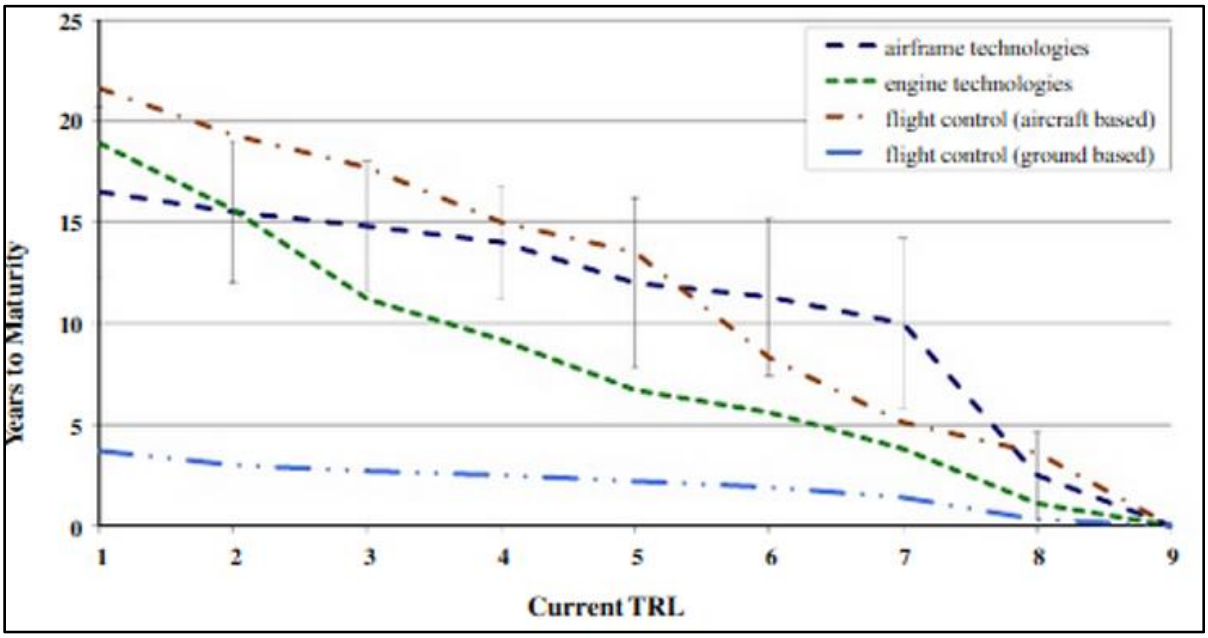


Figure 3: Aircraft Technology Readiness Level Timeline [44].

As said, in addition to historical data we can also scrutinise the maturing assessments conducted by other researchers. A TRL forecasting timeline can be found in a study carried out by the U.S National Academy of Sciences about technology development of unmanned ground vehicles (UGV) [43]. It has considered the maturing of three technologically different UGV's, named Donkey, Wingman and Hunter-Killer (Figure 4). The study predicts that for the least complicated system it will take four years to mature from TRL4 to TRL6, while it will require six years for the more advanced system and 16 years for the most advanced UGV. These results confirm the fact that the timeline does correlate with the technological complexity.

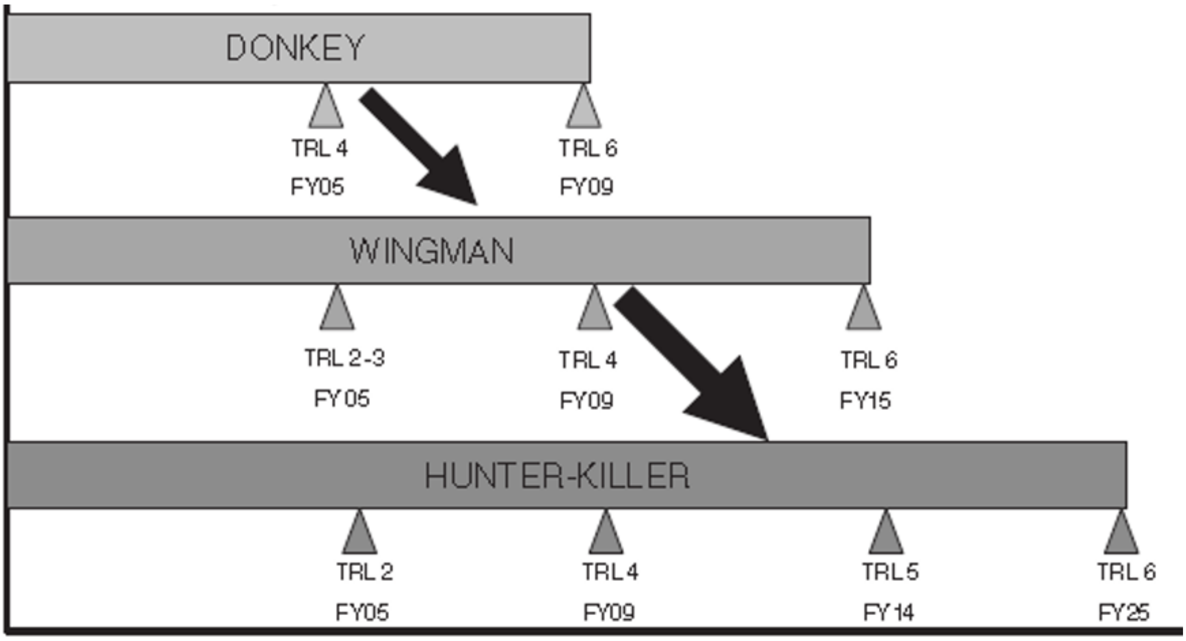


Figure 4: Forecasted UGV Technology Readiness Level Timeline [43].

Since the DEW systems are complex and include novel electronics, they must be regarded as representatives of advanced technology, and thus we must apply the longer timelines in forecasting their maturity. Based on the aforementioned this thesis uses the timelines for maturing as illustrated in Figure 3 but excludes the timeline of the ground-based flight control systems. The exclusion rests on the assumption that DEWs are more complex systems than and cannot be developed in such a short time.

3. LITERATURE REVIEW

As many other future technologies, DEW or ray gun at the time was first envisaged in the science fiction literature. Probably the earliest description of such a weapon was made as early as in 1898 [30]. As new technological breakthroughs were accomplished for example in the form of X-rays and microwaves, the film industry introduced us with more and more directed energy weapons.

In this chapter, an understanding of the directed energy weapon domain is gained by a thorough literature review. There are numerous different technologies utilised and researched within the field of directed energy weapons. Currently the DEW technologies include laser, maser and high power microwave/high power radio frequency (HPM/HPRF). However, based on thorough internet searches, only laser and HPM/HPRF can be now regarded as technologies capable of producing air defence weapons. Thus they are the technologies that this research focuses on.

First, the DEW is defined for this research, and this is followed by exploring the technological fundaments and the boundaries of physics affecting the DEW together with the introduction of the current DEW technologies and systems employing these technologies.

3.1. Defining Directed Energy Weapons

Since some slightly different definitions of directed energy weapons could be found, a single definition to serve this research was needed. For this purpose, it was decided to adopt the definition of the US Department of Defense Joint Publication 1-02 (JP1-02). This is based on the fact that US is currently the leading developer of DEW technology.

The JP1-02 defines directed energy as ‘an umbrella term covering technologies that relate to the production of a beam of concentrated electromagnetic energy or atomic or subatomic particles’ [75]. This definition indicates that no particular technology is excluded as long as it employs either concentrated electromagnetic energy or atomic or subatomic particles. In other words, DE encompasses entire frequency spectrum, depicted in Figure 5, from very low radio frequencies all the way to gamma radiation. It needs to be observed, however, that in weapon use some areas of the frequency spectrum are more useful than others and this brings us to the definition of Directed Energy Weapon.

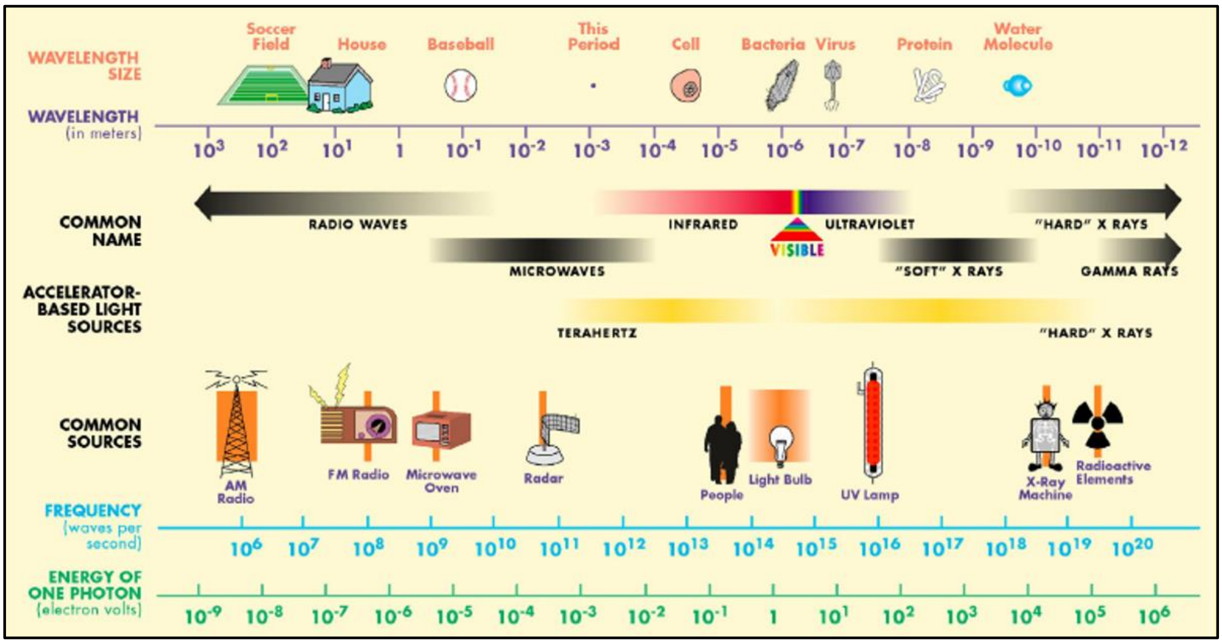


Figure 5: The Electromagnetic Spectrum [20].

Directed Energy Weapon is defined by JP1-02 as 'A weapon or system that uses directed energy to incapacitate, damage, or destroy enemy equipment, facilities, and personnel'[75]. As it is stated in the definition, a weapon needs to deliver an effect. To deliver an effect, there are some limitations regarding the used frequency. These restrictions are covered in the following sub-chapters. On the other hand, the definition also includes incapacitation as an adequate effect. According to dictionary 'incapacitate' is a verb defined as: 'prevent from functioning in normal way' [64]. This leads to a need for this research to also include systems which may prosecute the target by taking an indirect approach.

However, audio weapons, although fitting in the definition of DEW, are excluded. The exclusion is based on the assumption that audio weapons are incapable, even by indirect approach, to incapacitate, damage, or destroy air vehicles.

Another term that is often seen in discussions regarding DEW is 'non-kinetic weapon'. Although this term has several interpretations and definitions, it cannot be found in JP1-02. There may be several reasons why it has not been defined officially in JP1-02, which encompasses some 2500 entries, but it is likely to do with the confusion around the term. Although it may seem obvious in the beginning, the term was found to be a very tricky to define.

As an example a study conducted by Geneva Academy for International Humanitarian Law and Human Rights states a non-kinetic-energy weapon as ‘one that threatens or inflicts harm to a person other than through the application to the human body of the energy that a bullet, fragment, or other projectile possesses due to its mass and motion’[13]. Based on this definition, and its further elaboration [Ibid.], all DEW are non-kinetic weapons although not all non-kinetic weapons are DEW. This definition, however, leaves us with open questions regarding other aspects of non-kinetic.

For instance, when we familiarise ourselves with a list of families of weapons presented by US Navy 107[77]. Based on this classification kinetic weapons form one family of weapons while the other families are potential energy, directed energy, chemical and biological. According to this definition, all other than kinetic could be regarded as non-kinetic. Although this definition is logical unfortunately, it is not universal, and furthermore, it is noteworthy that there are DEW, lasers and particle beam weapons in particular, which can be seen to deliver kinetic energy to the target and thus considered as kinetic weapons [81]. Because of this, some directed energy weapons can be regarded as kinetic while some fall under non-kinetic. Therefore we cannot explicitly state that DEW’s are non-kinetic weapons.

This confusion has led to a suggestion to band kinetic energy, potential energy, and some directed energy weapons together and call everything else non-kinetic [Ibid.]. This view is useful in the context where weapon systems are discussed from a technical point of view and thus it is the one adopted by this dissertation too. Hence this paper does not categorise DEW under kinetic or non-kinetic weapons. This categorization depends on the particular DE technology since the family of DEW consists both kinetic and non-kinetic systems/technologies.

3.2. Laser

The laser is one of the two most prominent and likely DE technology to provide air defence effectors, and in fact, many demonstrators already exist. This chapter introduces the basics of laser technology in general while the primary focus is on laser’s military applications. However, the general principles of laser physics are valid regardless of the domain the laser is implemented in. Thus the fundaments remain the same although the requirements, e.g. for power, range, propagation, can differ drastically from domain to another [23] [51].

Lasers have been utilized successfully in numerous different areas of business and science as well as in the military for several decades. The range of applications is vast and ever expanding as new enhancements to current technology are introduced. Many of our daily appliances make use of lasers including remote controllers, motion sensors, bar code readers and DVD players, just to name a few. Naturally, the output power of these apparatus is minimal, and as such we may not even consider them as lasers. On the other end of the power spectrum we have industrial lasers capable of cutting and drilling, plastic, aluminium and steel. And somewhere in the middle, there are laser scalpels used for surgery.

There are two common nominators for all high power civilian lasers. Firstly there is the short range. The majority of the applications are used for distances less than 10 centimetres. Many are effective only if employed in distances less than a few centimetres or even millimetres. Despite there are few exceptions to this, in general, all the civilian lasers are very short range lasers. The other common nominator is that they are designed for indoor use where the ambient conditions are somewhat stable. As they are designed for extremely short distances and stable ambient conditions, they have enormous problems operating if either the distance is increased or atmospheric conditions are changed. We will cover reasons for these phenomena later in this chapter.

3.2.1. Principles of Laser

The term laser is an acronym meaning ‘Light Amplification by Stimulated Emission of Radiation’, and the principle was first introduced in 1959 [25]. Next, the principles and the unique features of the laser are discussed focusing on lasers applicability as a weapon.

The fundamental principle of the laser is based on the notion of spontaneous emission. In spontaneous emission, an excited state laser-active atom or ion may after some time decay into a lower energy level. This results in released energy in the form of a photon. In stimulated emission, this process is stimulated by incoming photons. In that case, a photon is emitted into the mode of the incoming photon. In effect, the power of the incoming radiation is amplified. This is the physical basis of light amplification in laser amplifiers and laser oscillators [51] [18]. This process is depicted in Figure 6.

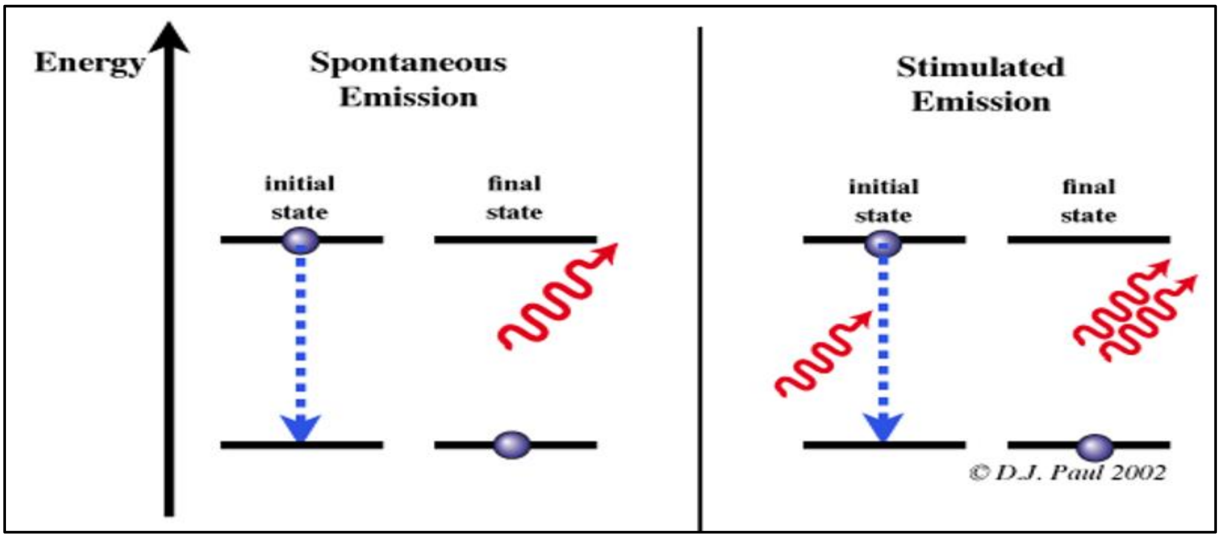


Figure 6: Laser Light Amplification [52].

For stimulated emission to provide an adequate amount of energy, the stimulation requires a process which is performed by a laser oscillator. It consists a gain medium, also called laser medium, which is either gas, solid or liquid and an energy input and an optical feedback mechanism. The optical feedback is usually generated by two mirrors on each end of the oscillator. On the other end, there is a fully reflective mirror whereas on the opposing end the mirror is partially reflective allowing some of the emission through [51]. A laser oscillator is portrayed in Figure 7.

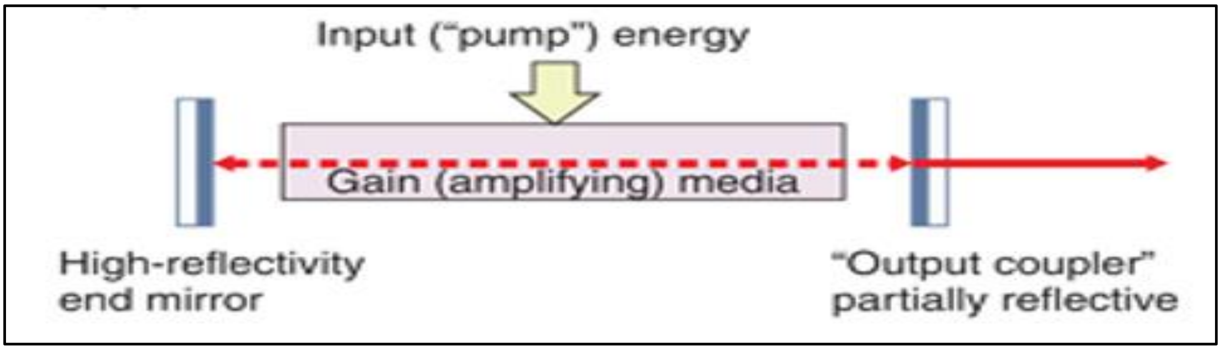


Figure 7: Principle of Laser Oscillator [12].

Laser medium's task is to add energy to the amplified light, and thus some energy must be provided to it. The laser medium is supplied with energy through a process called pumping. Pumping typically involves electrical current (electrical pumping) or a light input (optical pumping). For the amplification process to occur there is a requirement to maintain the majority of atom/ion population in the upper laser level. In other words, more laser-active ions are in the upper state than in the lower state.

This condition, where the majority of atoms/ions are in the upper laser level, is called population inversion [39] [18]. Population inversion is a state which differs from thermal equilibrium: in thermal equilibrium, the population of the lower level always exceeds the population of the lower level, and a positive net gain is not possible. Sometimes, population inversion is formally described as a state with a negative temperature. In many cases, it is achieved by optical pumping [51].

With an oscillator by itself, one can also reach very high power levels. The amount of amplification within an oscillator increases sharply with the distance travelled through the laser medium. It follows that we can increase the power by increasing the length of the laser medium. However, there some issues with that, specifically regarding linewidth, pulse duration and beam quality [51]. Hence there are systems, especially high power systems, incorporating amplifier/s. It follows that the use of amplifiers is often the case with laser weapons where high power is paramount.

Although laser oscillator does, in fact, amplify light, it is not regarded as an amplifier within laser terminology. A laser amplifier, also called Master Oscillator Power Amplifier (MOPA), is a separate apparatus to further amplify the seed laser. This process is illustrated in Figure 8. In the picture, the seed laser is produced by the oscillator which is then amplified to reach a higher power. There are a different kind of amplifiers utilising different technologies, and some laser applications utilise a number of amplifiers to reach the desired output power [51].

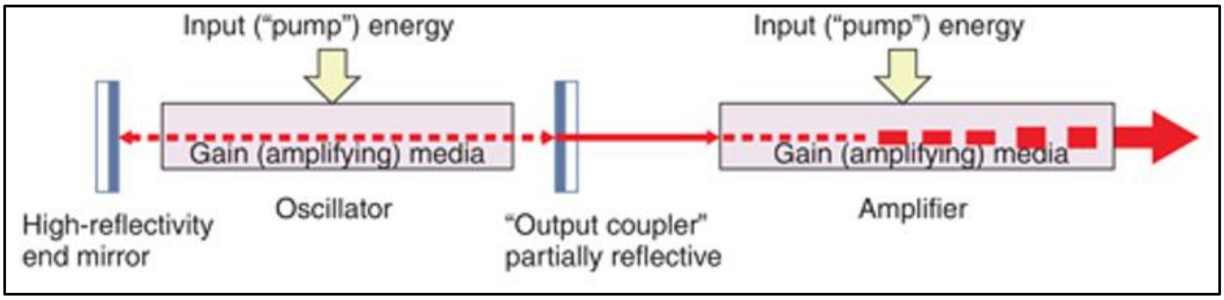


Figure 8: Principle of Master Oscillator Power Amplifier [12].

As was discussed, the laser has been found very useful in numerous domains and applications. This is the result of laser's unique features. The unique features of laser include [18]:

1. Directionality

   Contrary to normal visible light laser light has a unique character of radiating to a particular direction. Hence there hardly is any divergence of emission and energy can be transferred efficiently and power losses are minimal. [23]

2. Monochromaticity

   The linewidth (bandwidth) of the laser is extremely narrow compared to other light sources. Narrow bandwidth means the range of frequency is narrow which results in single spectral colour. This does not, however, mean all lasers operate at the same frequency. On the contrary, a laser device can operate in any spectral frequency, and some lasers can even change the frequency. [23]

3. Coherence

   Coherence is a vital concept in optics and is strongly related to the ability of light to exhibit interference effects. Light is called coherent when the waves have a constant relative phase. Lasers have the potential for generating beams with very high spatial coherence, and this is perhaps the most fundamental difference between laser light and radiation from other light sources. [51]

3.2.2. Types of High Energy Lasers

In general high energy lasers (HEL) are categorised into four classes. These are Solid State Laser (SSL), Dye/Liquid Laser, Gas Laser and Free Electron Laser (FEL). These categories incorporate lasers utilising different kinds of technology and laser medium each with unique characteristics [33]. These laser types and their characteristics are discussed next.

Solid State Lasers:

Solid state lasers utilise, as the name suggests, solid lasing media like ceramic or glass-like solids. The very first laser was, in fact, a solid state laser. The SSLs are further subcategorized into four groups; watt class, bulk lasers, fibre lasers and disk lasers. The watt class are the most commonly used lasers both in civilian and military applications. The military applications include, for example, range finders and laser radars. This technology is very mature and somewhat pervasive.

Bulk laser refers to a big lasing medium as opposed to the fibre lasers non-bulky fibre lasing medium [51]. Bulk lasers can reach over 100 kW output powers. Multiple bulk lasers can be combined and aligned together to provide higher power. Fibre laser, on the other hand, utilises a long optical fibre to generate the laser output. Fibre laser enables smaller size and costs compared to bulk lasers. Further benefits include better heat radiation and overall heat generation due to better wall-plug efficiency [1]. Multiple fibre lasers can be connected to increase output power too, and a single fibre laser can currently produce outputs of approximately 10kW. The fourth class are the disk lasers which have been named according to the very thin disk they use as the lasing medium. They compete with fibre lasers and possess similar advantages with them. However, disk lasers also possess features that cannot be reached by current fibre laser technology [51].

Dye/Liquid Lasers:

A dye laser uses a dye as the lasing medium. Organic molecules in liquid form compose the basis for most laser dyes, albeit solid and vapour laser dyes exist. Since the dye is in most cases liquid, Dye lasers are also referred as Liquid lasers [51]. The terms are, however, not interchangeable, since Liquid laser explicitly refers to liquid only. It results that, the liquid laser is a sub-category of Dye lasers. As far as weapon solutions are concerned the main feature of Dye lasers is the ability to exhibit a broad gain bandwidth. This enables wavelength tunability which can be used to mitigate weather related energy attenuation.

Gas Lasers:

There is a variety of different gas laser types. Chemical lasers use energy-liberating reactions of chemicals in their gas phase. Their characteristics include massive size and weight as well as laborious and challenging fuel management [33]. The fuel management issues derive from the use of the highly toxic chemical. Currently, chemical lasers are the only type of laser that has been able to produce very high powers ranging from several hundreds of kilowatts to a megawatt [1]. In spite of the high power, the chemical lasers' deficiencies are currently viewed insurmountable and thus majority of military chemical laser programmes have been cancelled.

However, in spite of the problems encountered by chemical lasers, there is another gas laser type that the military domain is now looking into. A promising development path has been opened by implementing vapour metal laser technology. It has been suggested that alkali-vapour laser's high efficiency and can be combined with commercially available diode arrays.

This is seen to provide accelerated maturing to tactical systems, with superior mass-to-power ratios compared to current laser systems [36] [38].

Free Electron Lasers:

Free electron lasers are the possible future technology of laser weapons. The technology is currently very immature and is assessed to sit between TRL 2 and 3 [33]. FEL systems are massive in size, and their current demonstrated output power is in the 20kW range. Their positive features include a potential for very high power and the ability to tune their beams to different wavelengths. The tuning ability is something of high interest in the military applications as the propagation window fluctuates and the FEL could compensate this by being able to follow the window.

3.2.3. Laser as an Air Defence Weapon

There are numerous attributes that an air defence effector must possess. As for the purposes and scope of this research, we focus on the laser system's ability to inflict desired effects to the target. These effects are related to the amount of energy delivered to the target system. Since aerial targets are fast movers in nature the targets exposure time is in many cases very limited. As there is a limited timeframe in which the required energy must be delivered to the target, there is a need for very high power. Furthermore, as the size and form of aerial targets range from mini/micro UAS to fighter jets and beyond, the effectors' output power requirements are target dependable. The following table gives a rough idea of the necessary power in relation to the target. It does not by any means give exact figures but provides the reader rough estimates of the necessary power. Based on the table, this study assumes the threshold power for downing manned aircraft is 500kW.

SOURCE	BEAM POWER MEASURED IN KILOWATTS (kW) OR MEGAWATTS (MW)				
	~10 kW	TENS OF kW	~100 kW	HUNDREDS OF kW	MW
NAVY BRIEFING (2010)	UAVS				
		Small Boats			
				Missiles (starting at 500 kW)	
SECOND NAVY BRIEFING (2010)		Short-range operations against UAVs, RAM, MANPADS (50 kW - 100 kW; low BQ)		Extended-range operations against UAVs, RAM, MANPADS, ASCMs flying a crossing path (> 100 kW, BQ of ~2)	Operations against supersonic, highly manueverable ASCMs, transonic air-to-surface missiles, and ballistic missiles (>1 MW)
INDUSTRY BRIEFING (2010)		UAVS and small boats (50 kW)	RAM (100+ kW), subsonic ASCMs (300 kW), manned aircraft (500 kW)		Supersonic ASCMs and ballistic missiles
DEFENSE SCIENCE BOARD REPORT (2007)		Surface threats at 1-2 km		Ground-based air and missiles defense, and countering rockets, artillery, and mortars, at 5-10 km[a]	"Battle group defense" at 5-20 km (1-3 MW)
NORTHROP GRUMMAN RESEARCH PAPER (2005)	Soft UAVs at short range	Aircraft and cruise missiles	Soft UAVs at long range	Aircraft and cruise missiles at long range, and artillery rockets (lower hundreds of kW) Artillery shells and terminal defense against very short range ballistic missles (higher 100s of kW)	

Table 3: Power Requirements for Different Target Types [20].

The table indicates that should the laser be able to engage all current air defence targets there is an output power requirement ranging from 10 kilowatts to several megawatts. All of the output powers stated in the table are, nonetheless, considered very high although there is no universally agreed definition what exactly is a high-power laser [51].

As said, the table is very general in nature, and variables like range are stated ambiguously only indicating that the power requirement increases when range increases. Range does come with other issues too, some of the most significant being the beam quality and the tracking accuracy. We can draw some conclusions of the range related issues by the following example of soldering lasers.

Since civilian high-power soldering lasers generally operate in distances of a less than few centimetres the beam quality is not a factor, but it becomes one when remote welding is in question [39]. And in remote welding, we are talking about distances of only 1-2 metres. So it is evident that beam quality is paramount in air defence scenarios where the ranges are 1000+ metres. Furthermore, the target of the welding laser (welded object) is stationary, which is not the case in air defence scenario. Thus accurate tracking is required to hold the beam tightly in the same spot, and this understandably gets trickier with distance, also keeping in mind that the intention is to engage a moving and possibly manoeuvring target.

Whereas power output is a significant factor it is by no means most important. As the term, HEL suggests it is the amount of energy what matters. Hence we cannot derive lasers effectiveness based on power, but we need to find out the fluence of the laser. Fluence is the amount of energy concentrated in a given area over a particular distance. Its most common units are J / cm^2 (joules per square centimetre) [51]. To give the perspective of applicable fluence values, it requires a fluence of $5000J/cm^2$ to penetrate a 3mm thick aluminium plate whereas optical sensors can be damaged by as low fluences as $10J/cm^2$[57].

3.2.4. Laser Weapons under Development

As was said there are numerous military applications making use of a laser. Laser technology has proliferated all over the spectrum of military operations, and some applications have been around for decades. As an example, the military utilises lasers for range finding, target designation, sensor dazzling and as sights. Alongside with the supporting tasks mentioned the military has been very keen in developing lasers to perform as weapons. This development has led to some promising concepts, and several actual high energy laser (HEL) demonstrators have been showcased over the course of the years. Already in 1990, a HEL system was able to down missiles and supersonic vehicles. This system, however, known as Mid-Infrared Advanced Chemical Laser (MIRACL), had several drawbacks including size, cost, propagation problems and risk related to hazardous chemicals [42]. The same issues were factors also for other laser systems that have demonstrated high power engagement capability [65]. These systems include Tactical High Energy Laser (THEL) developed by US Army and USAF programme called Airborne Laser (ABL). They all utilised chemicals as a laser medium which meant they were able to reach high power but suffered from problems related to the highly toxic chemicals. All this meant there was still a long way to an operational system.

Following the fundamental deficiencies of chemical lasers the research and development efforts are currently mostly directed to Solid State (SSL), and Free Electron Lasers (FEL) and the majority of military grade lasers in demonstrator phase are SSL’s. FEL is the technology of tomorrow, and currently, they are hugely expensive and large.

A selection of the most prominent ongoing and cancelled laser weapons programmes are presented in Table 4. The table is a compilation of the most interesting systems, arranged in order of the type of laser, describing current status and goal of development programmes based on several sources [14][20][33][50]. Some detailed information has been added to the table using other sources too. These references can be found within the table. The table is not exhaustive but provides an overview of the current situation and allows further analysis to be made regarding for example technology, maturity, timescale and possible targets.

Programme Name	Laser type	Purpose	Status	Goal
FEL (Free Electron Laser)	FEL	Technology maturing programme	Early stage technology programme MIT & Arizona state [2]	1MW+, 1 meter length,
ABL (Airborne Laser)	Gas	Strategic missile defence	Cancelled	Several MW's, hundreds of km range
ATL (Advanced Tactical Laser)	Gas	Gunship (AC-130) A/G weapon	Cancelled	100kW+
DPAL (Diode Pumped Alkali Laser)	Gas	Strategic missile defence, ballistic missiles in boost phase	20-30kW, 20-30kg/kW	1MW+, 2kg/kW [38]
HELLADS (High Energy Liquid Laser Air Defense System) [61][31]	Liquid (Dye)	Air Force, A/G, self-protection	Developmental, entering field trials	150kW+, weight less than 5kg/kW
GBAD DE OTM (Ground Based Air Defence Directed Energy On The Move) [48]	N/A	Integration of several systems to one complete weapon system.	Field trials in 2017	UAS engagement capability for expeditionary forces (Marines). 30-50 kW.
HELE/LWM (High Energy Laser Effector/Laser Weapon Module) [54]	N/A	Rheinmetall's self-financed technology programme	Developmental, Demonstrator 3x10kW. Successful engagement of UAV and RAM	
TLS (Tactical Laser System) [7]	N/A	Ship self-protection. UAS, light targets	10kW demonstrator in 2011.	
LDEW (Laser Directed Energy Weapon) [72]	N/A	UK MOD funded programme for a capability demonstrator	Started 1/2017	Demonstrator in 2019. Possibly leading to in service weapon in mid-2020.
Gamma [46]	SSL	Northrop Grumman self-financed technology programme	Initial test in 2012 13,3kW units that can be combined	
HEL MD (High Energy Laser Mobile Demonstrator) [26]. Follow-on programme called HELMTT 105[53]	SSL	Proof of principle for mobile GBAD DE for Army. HELMTT will use RELI's laser system.	successful test of 10kW	50-100kW. G-RAMM capability.
MLD (Maritime Laser Demonstrator) [47]	SSL	Ship self-protection	Demonstrator utilizing JHPSSL in maritime conditions. 105kW in 2009.	No stated project goal. 300-600kW is considered achievable.
JHPSSL (Joint High Power Solid state Laser)	SSL	Joint technology programme. Leveraged by Navy in MLD.	105kW in 2009.	
Excalibur	SSL/Fibre	Scalable multipurpose laser system for air vehicles (A/G, self-defence, missile defence	Developmental, demo in 2013	100kW+ [41]
LAWS (LAser Weapon System) [47]	SSL/Fibre	Ship self-protection	Prototype 30kW, installed on USS Ponce	100kW+ IOC stated for 2020-2021
RELI (Robust Electric Laser Initiative) [69]	SSL/Fibre	Laser programme for US Army and Air Force operated platforms		Weight less than 7kg/kW, 30% wall-plug efficiency, 100kW+

Table 4: Laser Weapon Programmes.

3.3. High Power Radio Frequency Weapons

Another prominent DEW technology is High Power Radio Frequency (HPRF) weapons. They are also commonly referred as High Power Microwave (HPM) weapons, High Power Electromagnetic Weapons (HPEW) or non-nuclear Electromagnetic Pulse (EMP) weapons. These terms are more or less interchangeable [20][57][8], and this thesis adopts High Power Radio Frequency (HPRF) as the used term.

In simple terms, HPRF weapons transmit RF energy to affect the target. The effects depend on the power, distance and the target itself and in some cases the operator can decide the effects by choosing the desired engagement power. The ultimate design goals of HPRF weapons range from crowd control to downing UAS or disabling electronic devices. As this thesis is on air defence, we will focus systems capable, or designed to be, of prosecuting air targets.

3.3.1. Principles of High Power Radio Frequency Weapons

There are two categories of HPRF weapons; an HPRF weapon system and an HPRF munition. An HPRF weapon consists of a power source, transmitter and an antenna. The apparatus sends energy towards the target, and the target is either permanently incapacitated, or its ability to conduct its mission is prevented. [57]

An HPRF munition also referred as an e-bomb or microwave munition, is a munition encompassing a conventional explosive material which primary task is to provide energy for the embedded microwave device. The device transforms the energy into high power RF radiation to incapacitate nearby electronics. Speculations state that HPRF munitions, 900kg bombs, were used already in the first Gulf War [32]. Open literature does not mention air defence variant of HPRF munitions. However, this is one theoretical future development once adequate power outputs can be reached with anti-aircraft size munitions.

The effect on an air target can be obtained either by molecular heating or electrical stimulation. Molecular heating is based on heating the target to the point where its fuel or explosive payload will explode or set on fire. The desired effects can also be reached by degrading the air vehicles structures due to intense heat. Molecular heating requires extensive dwell time on target, and thus it is not very likely approach against fast moving air targets.

Electrical stimulation, however, requires far less power and dwell time thus being more feasible for air defence engagements. In electrical stimulation, microwave energy connects with any material conducting electricity and stimulates electron flow in the material. This electron flow produces transient currents and voltages. Target's electrically conductive materials act like little antennae gathering the high power. Transient currents interfere with the normal operation of electrical components, inducing specious signals that confuse the system or even damage sensitive components.

US Air Force Research Laboratory has divided the effects of HPRF weapon into four categories: upset, lockup, latch-up and burnout [20]. These are introduced below.

Upset *is a temporary alteration of the electrical state of one or more nodes in such a way that they no longer function normally. Once the signal is removed, however, the normal function returns with no permanent effects. Jamming is an example of this type of effect, where a sensor might lose lock because of interference.*

Lockup *produces the same effects as upset, but an electrical reset is required to regain functionality, even after the signal is removed. If a computer were to freeze after exposure to an RF signal so that it had to be rebooted, this would be an example of lockup.*

Latch-up *is an extreme form of lockup in which a node is permanently destroyed, or electrical power is cut off to the node. A fuse blowing or transistors failing on a circuit board due to overloads from microwave radiation are two such examples.*

Burnout *is the physical destruction of a node where the current becomes so great that conductors actually melt. This usually occurs within smaller wires or at junction nodes where multiple wires come together and often involves electrical arcing. The damage to household electronics caused by a lightning strike is an example of burnout.*

In broad terms, burnout requires, depending on the component class, from 1000 to 10000 times more power than upset. Burnout power levels are in the 100W region whereas upset can be accomplished with 0,1W or less [57].

All of the effect categories are purposeful in military applications. In a GBAD scenario, they all can oppose a precision attack by disrupting or disabling either the weapon system or the platform itself. The more powerful effects like burnout and latch-up are most sought for as they will inflict permanent damage to the target. This is specifically the case when the target is the platform since both burnout and latch-up will require laborious repair and maintenance keeping it grounded for a very long time.

Whichever effect discussed above is sought the signals transmitted by HPRF weapon must reach vulnerable components of the target. These components can be reached directly via targets sensors, such as the antenna or seeker head, or indirectly through the target's body. The direct method is referred as ‘front-door coupling’ and the indirect as ‘back-door coupling’. The principles of the methods are depicted in Figure 9. [57]

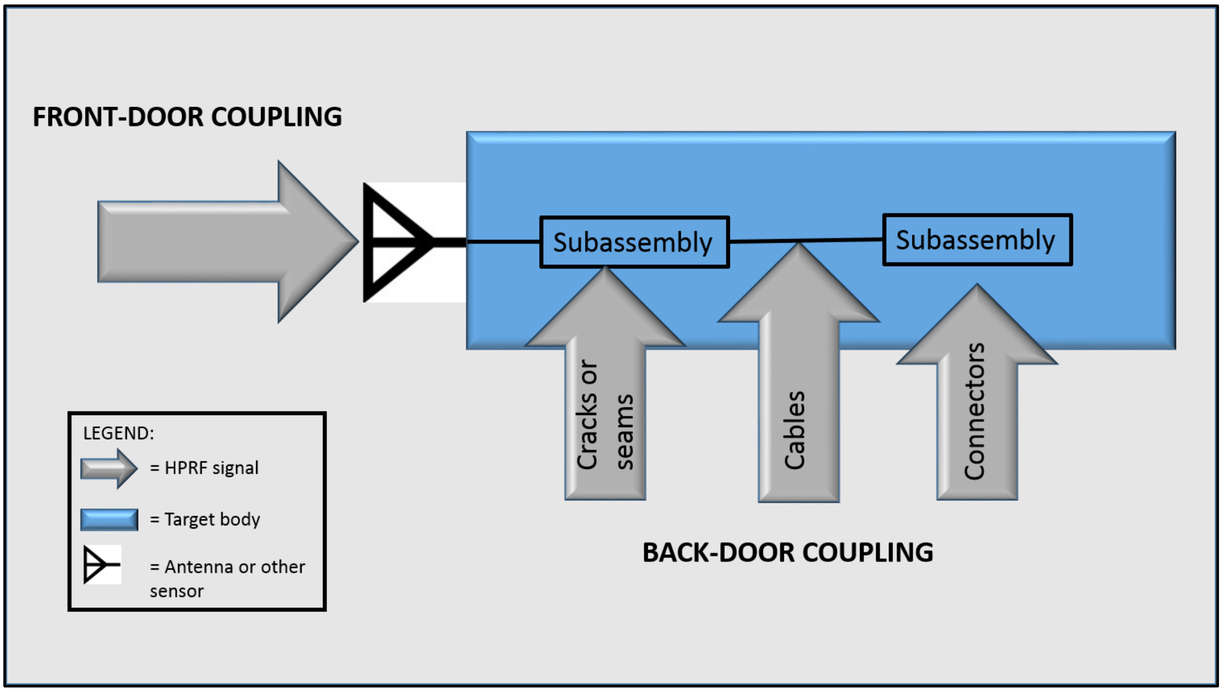


Figure 9: Principles of Front-door and Back-door coupling [57]. Adapted from [3].

Front-door coupling is most efficient when the target system’s receiver is operating in the same bandwidth as the weapon. This is because target’s antenna is designed and tuned to receive signals of particular bandwidth and thus it is very susceptible to malicious signals of the same bandwidth. Although in general, the inflicted damage has a direct relation to the power of the HPRF signal this is not applicable when targeting radar systems. This results from radar’s built-in limiting devices protecting the receiver from radar’s transmitter.[57]

As the name suggests, back-door coupling takes advantage of HPRF signal’s ability to penetrate the skin of the target system. Albeit the skin provides some protection itself, it is still possible to inflict desirable effects to target’s electronics. Once inside the target system, HPRF signals cause drastic issues for the circuitry. Due to target's protective casing, back-door coupling requires more power than front-door coupling.[57]

3.3.2. HPRF Weapons under Development

The HPRF programmes identified by the literature review are presented in Table 5. It is noteworthy that publicly available information about HPRF weapons is limited and general in nature. The number of systems mentioned is only five compared to some 20 laser system programmes introduced earlier. It also became evident air defence has not been the developers' main interest as only one HPRF system was designed for downing air vehicles. All four identified systems are designed for other purposes than air defence. Nonetheless, if they can mature the technology itself, it may be transferrable to future air defence systems.

We can only speculate the reasons what comes to the little number, prominence and publicity of HPRF systems/programmes found. However, there are sources speculating that although the theoretical principles and applicability were established several decades ago, there just is too many technological hurdles to be surpassed [79].

Programme Name	Purpose	Status	Goal
Active Denial System[20]	Counter-personnel/Crowd control	Deployed to operation in 2010. Never used in operations. Withdrawn from field and not in use.	Controlling rioters/crowds from a distance of some hundreds of meters without inflicting permanent damage. Goal met.
NIRF (Neutralizing IED's with Radio Frequencies)[20]	IED neutralization	Unknown.	Incapacitating IED electronics from a safe distance.
MAXPOWER[20][6]	IED neutralization	Unknown.	Incapacitating IED electronics from a safe distance.
CHAMP (Counter-electronics High-powered Advanced Missile Project)[20][60]	Incapacitation of electronic targets/systems	Flight test in 2012 with engagement of soft electronic targets.	Deliver microwaves from an aircraft or missile, effectively walloping a target's data and electronic subsystems.
HPM Demonstrator [29]0	Counter UAS	Engagement test in 2013. Successful downing of small UAVs.	Unknown.

Table 5: HPRF Weapon Programmes.

3.4. Advantages and Disadvantages of DEW

As it is with all weapon system, DEWs also come with both positive and negative features. In this chapter, we look into the positive and negative features of DEW. These encompass both technological attributes as well as notions related to usability and deployability. First, we look at the positive characteristics and then familiarise ourselves with the negative ones accompanied with technological issues identified by the literature.

3.4.1. Strengths of DEW

Collateral damage reduction is an advantage which is often mentioned regarding DEW. Both laser and HPRF systems can engage the targeted system with a remarkable accuracy and since there is no kinetic force the proximity of friendly forces is not an issue. Furthermore, DEW's can provide an option for non-lethal engagement by offering 'scalability' of effect.

Infinite magazine; this term refers the DEW's ability to engage targets without a need for reloading, and it is often seen advantageous feature especially in countering swarming attacks and salvo attack [20]. DEW's can fire as long as their electricity supply is working.

Another positive characteristic is that the effector beam or signal is travelling *speed of light* [33]. This is advantageous in countering salvo/swarm attacks as the system can engage numerous targets in a short period. This is because there is no delay in waiting that the ammunition or missile reaches the target before a new target can be engaged. Furthermore, rapid engagement leaves little or no time for countermeasures.

Engagement price of DEW is extremely low, it only requires electricity but no projectiles. Whereas state-of-the-art GBAD ammunition cost tens of thousands euros per burst and missiles from hundred thousand to several million, the price of a DEW engagement costs approximately one euro. Not only are there the obvious saving benefits but also the fact that DEW's enable engagement of low cost targets and turns the cost ratio of countering swarming/salvo attacks favourable for the defender.

HPRF weapons allow *engagement of several targets simultaneously* with a single system. This is possible because of the relatively big divergence angle of HPRF transmitter widening the beam radius to several hundred meters in a distance of 2 km [33]. The wide beam also means less strict requirements for target tracking which is quite the opposite in laser's case. In addition this feature could also enable engagement of stealth targets without a precise track.

Silence is another advantage the DEW possess. Depending on the mission type and scenario it is seen as very interesting feature as it enables covert operations [31]. Silence is also advantageous feature in many other uses too; for example, the current C-RAM systems used for camp protection can cause hearing damages to bystanders as they are unaware the system will fire. This will not be an issue with DEW systems.

The widespread use of DEWs l*ower the logistics burden.* The required effort to supply a DEW with fuel is much less than what is required to replenish ammunition for a gun system. Furthermore, there is no need to upkeep ammunition storages or worry about the aging of ammunition.

3.4.2. Weaknesses of DEW

Size, weight and power (SWaP). Based on several factors laser systems currently struggle with SWaP related issues. Although SWaP- issues are a factor with many new systems and technologies, DEW, and laser, in particular, have numerous SWaP concerns to surmount. The reasons behind these issues are discussed next.

Power requirements. Due to current laser wall-plug efficiency of around 20% [33], one requires an input power of 500kW to produce a 100kW laser beam. Based on the power requirements presented in Table 3 an input power of some 2-5 MW is required for engaging aircraft size targets. The power requirement is one of the reasons why currently most advanced laser systems are installed on ships. And even then there are major limitations regarding power.

The current power distribution system of battleships is not able to provide enough power for the high power laser systems. The modern US Navy combat ships could accommodate a maximum of 100kW laser system in battle conditions [47]. In the future, when the all-electric-drive has become a standard in battleships like the Zumwalt-class already has, this issue will be surmounted [28] [27]. The Zumwalt-class with some 58MW of power available [50] for weapon systems will be joined by at least the future Gerald R. Ford-class aircraft carriers which are initially designed to provide 300% more power than the current Nimitz-class [50]. This will most likely be a new norm for the future combat ships.

Another SWaP related topic is the *weight*. Today's DEW systems' mass-to-power ratios are in the ballpark of 35-55kg/kW meaning that a Megawatt class laser apparatus would weigh at least 35 tonnes and a 100kW device some 3,5tons. The latter is not a big problem as long as the desired effect is reached with 100kW. But as we can see from Table 3, 100 kW will suffice in close-range UAV engagements only. There are, however, big expectations regarding the development of lighter systems and the targets for mass-to-power ratios are as low as 2kg/kW as can be seen in Figure 10.

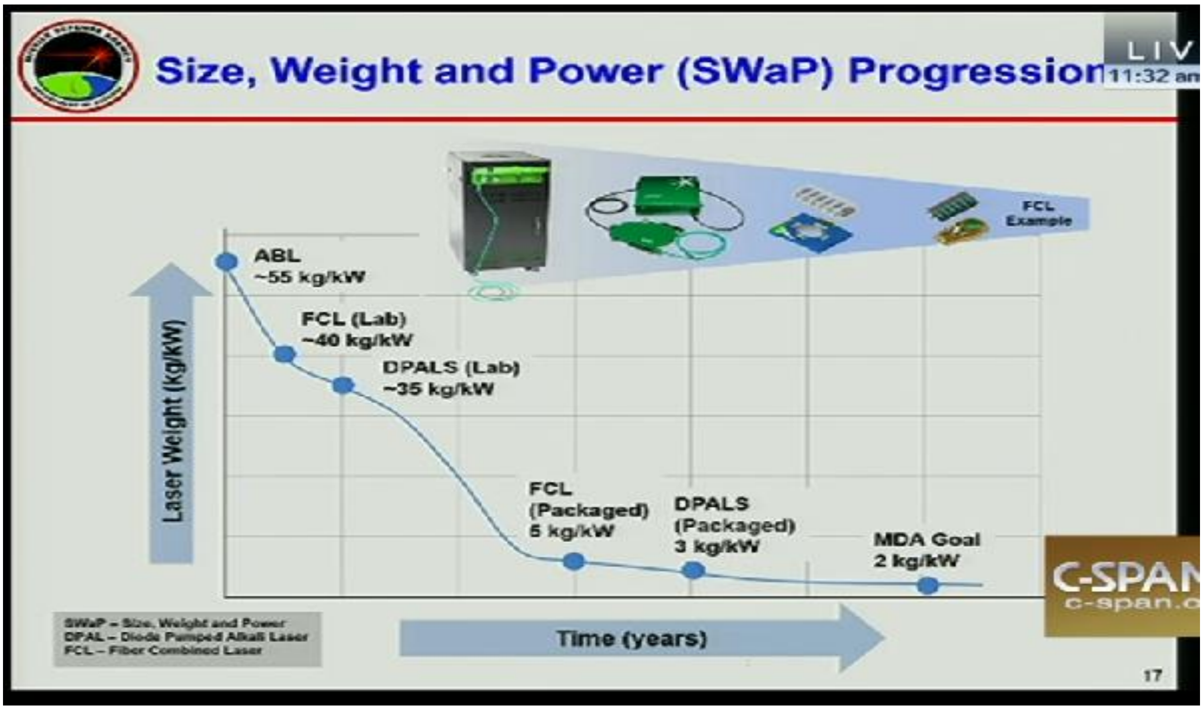


Figure 10: SWaP Progression Plans of US Missile Defence Agency [67].

Along with to the mentioned weight issues comes the *size* issues. Accommodation of a laser system requires new design even for ships [33]. Again this is an even bigger problem when aircraft or mobile ground systems are in question. A reduction in size will eventually follow as the technology evolves but this will take time.

Heat is a direct result of poor wall-plug efficiency. Since some 80% of electrical power is wasted in the process of generating a laser beam, there is a need for expensive and space-consuming cooling unit [33] [20]. This is a factor especially with ground-based systems as well as with airborne systems. This likely is another reason why today's laser weapons are mostly shipborne. Another issue resulting from heat is the systems high IR signature which can be a major problem in the battlefield. Hence it is not enough only to solve the cooling; one must also retain the systems IR signature at an acceptable level.

Due to the extreme narrowness of laser beam *precision tracking* is vital to provide desired effect. Without an exact and stable tracking, big part of the beam's energy is lost as it is not concentrated on a single point [57]. Precision tracking increases both size and complexity of the system. It is noteworthy that this applies to laser systems only as HPRF use a wide beam as mentioned earlier.

Some literature considers *collateral damage and fratricide* as a possible worry when DEW are used [17] [33]. This is mainly related to HPRF which cannot differentiate between hostile and friendly systems but affects all electronic systems in the direction of the signal.

Both HEL and HPRF require a *line of sight* to the target, otherwise, the energy cannot reach the target. This becomes an issue when engaging a target beyond the horizon and also when using HEL to engage low flying targets partially obscured by obstacles such as trees or buildings. The line of sight issue can be mitigated with relay (airborne) mirrors, but this further complicates the system [20].

Range limitations are of course scenario and requirement dependable. However, as we focus on GBAD, there is a need to engage targets at least in the 5km range and beyond. This is currently a challenge, as demonstrated ranges are less than 3km. Furthermore, effective range is heavily dependable on the targets aspect angle (see Table 3).

Currently, DEWs suffer from *weather limitations* because certain atmospheric conditions decay wave energy [33] [57]. This especially applies to HEL, but HPRF does not come without problems either. Technological advances will most likely overcome this issue partially, by introducing wavelength tunable laser systems.

3.5. Recent DEW Maturity Surveys

Since the DEW's have been coming of age for a few years now, there are some unclassified polls that have covered the maturity of DEW in the years to come. Two of these are presented next.

A company named Defence IQ conducted a poll before an annual DE conference which the company organises. Although the survey can be regarded as a conference advertisement and does not include year estimates, it does provide some insight of DEW topics. The survey was sent to more than 300 people, but the report does not state the number of respondents. This is a fact that should be kept in mind when the answer percentages are viewed. Out of the respondents, 31% were military, and 25% represented the industry. In the following, the results of two of the most interesting questions related to this thesis are introduced. [17]

In the first question the respondents were given a set of factors and asked to identify biggest obstacles for DE systems' proliferation. It is not clear how many factors the respondents were allowed to choose but it was more than one as the total percentage exceeds 100. The answers, illustrated in Figure 11 reveal five factors that were regarded most likely. These are 1) user safety/fratricide concerns 2) lack of understanding of integration with legacy systems, 3) lack of understanding of DE capabilities/requirements, 4) lack of funding and 5) lack of technological reliability (e.g. blooming).

Figure 11: Results of Defence IQ Survey Question 1[17].

The other question regarding DEW maturity in Defence IQ's survey asked the respondents to choose the most important technological issues. The answers to this question are depicted in Figure 12. The three issues identified as most important were: 1) collateral damage risks, 2) inability to control blooming and 3) usability in inclement weather. Again the numbers behind the percentage are not stated. Thus we cannot assess the validity as such.

Figure 12: Results of Defence IQ Survey Question 2 [17].

The second study was made for Center for New American Security by Ben Fitzgerald and Kelley Sayler in 2014. This study asked DEW maturity related questions from a total of 1019 participants, of which 71% had experience in the national security realm and 45% were either serving or retired military. The poll was conducted in 2014 and had an average of 340 respondents. The study consists two DEW related questions which, together with the answer distribution, are presented and discussed next. [24]

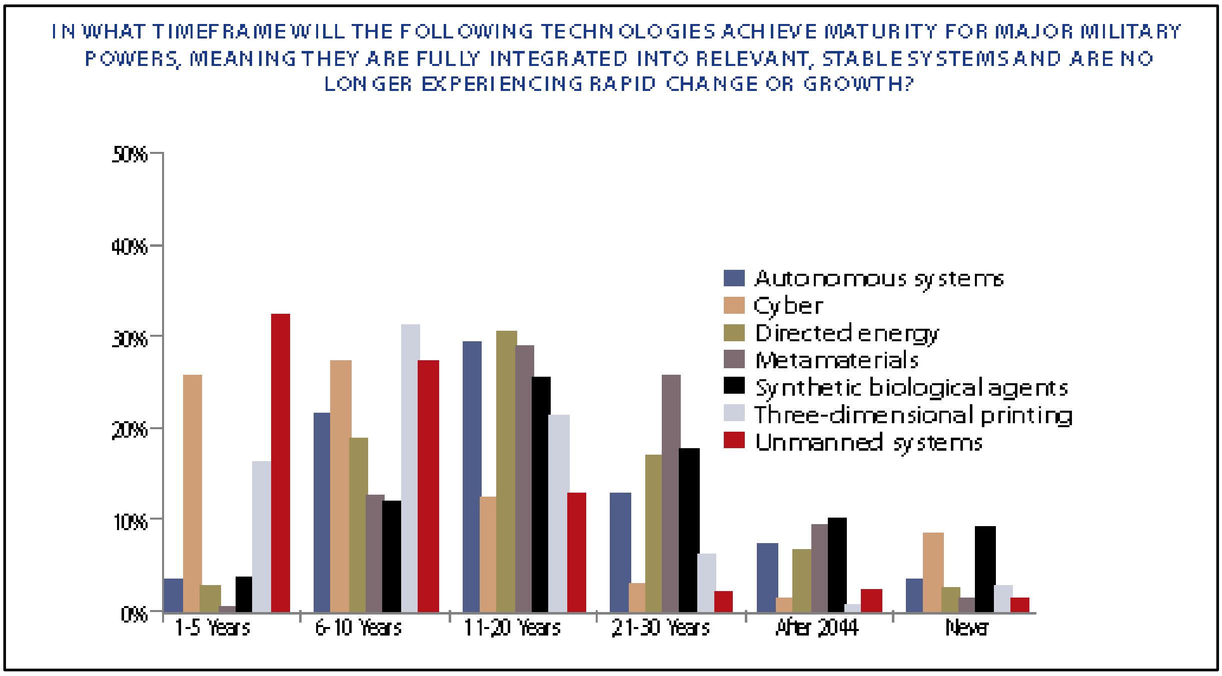


Figure 13: Answer Distribution of CNAS Poll DEW Question 1 [24].

The distribution of answers, depicted in Figure 13, indicates some agreement. It should be noted that some of the replies seem to be missing as the sum is roughly 80% although it should be 100%. Despite this discrepancy, we can draw some conclusions of the distribution of answers. The bar chart states, as an approximate since we do not have the exact figures available, that some 50% consider DE being fully integrated into stable military systems by 2034 while 30% assess it will happen later or never. Although we do not know what the missing 20% have answered, we can still conclude that the mean of answers seems to fall somewhere between years 2025-2035.

However, the question itself is ambiguous and could have been interpreted differently by the respondents. As an example, the question asks to consider the situation when a 'technology is no longer experiencing rapid change or growth'. This can be seen as a situation when DEW is fully mature and capable of engaging a wide portfolio of targets, but it also can be seen that DEW technology is fully mature and will no longer develop but is still incapable of providing a meaningful military effector. Furthermore, as for this thesis' focus, we cannot derive conclusions regarding how the respondents regarded the maturity and capability of DEW in GBAD role. This implicitness is visible in the next question too.

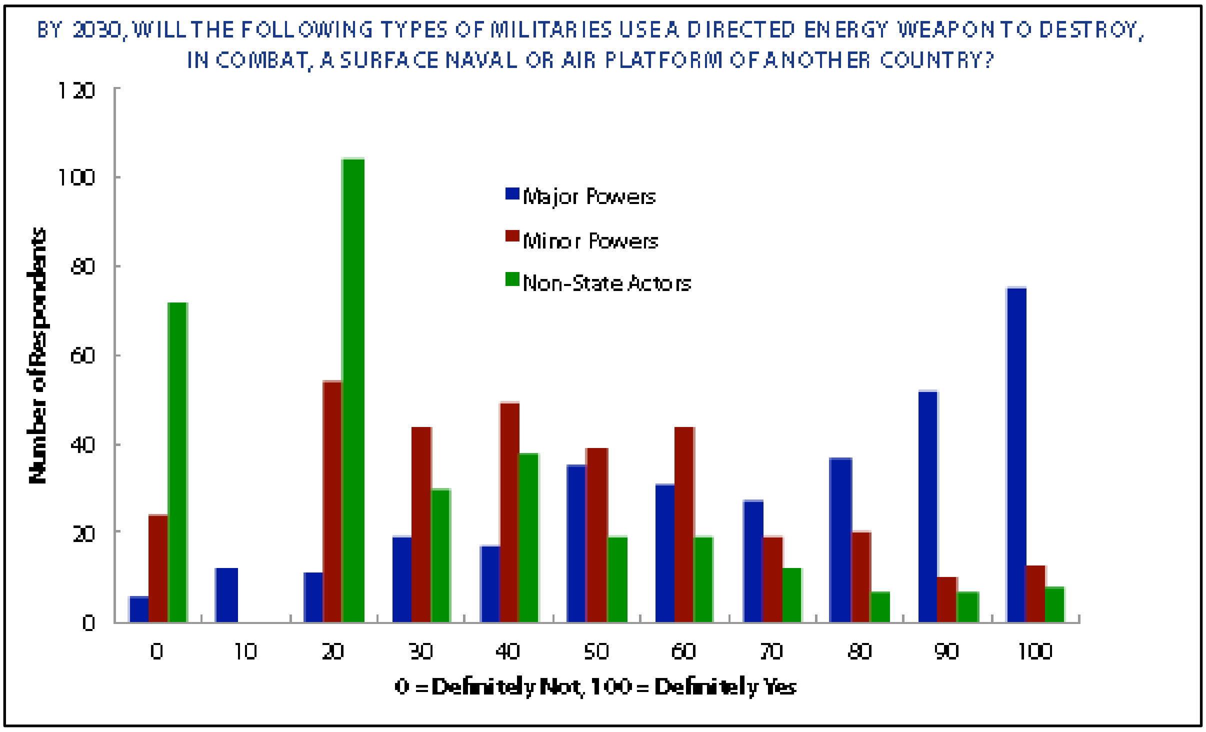


Figure 14: Answer Distribution of CNAS Poll DEW Question 2 [24].

The answer distribution of the second DEW related question in the CNAS study is shown in Figure 14. It should be noted that in this bar chart the results are shown in numbers of respondents not in percentages as was in the previous chart. The results indicate relatively strong confidence that directed energy weapons will be mature enough to be used by major powers in combat to destroy either air or sea platform by 2030. Approximately 2/3 (229) of the respondents consider the scenario at least moderately likely, whereas 1/3 foresee the scenario unlikely. Again, as there is no further explanation of the type or size of the target to be destroyed, there are some equivocality issues with the results. It is impossible to assess what kind of target the respondents considered while answering and thus we cannot draw conclusions on how they perceive DEW ability to down manned aircraft size targets for example. Nonetheless, the results do indicate a relatively clear consensus that there will be fielded and deployed DEW systems by 2030.

3.6. Conclusions of the Literature Review

The scientific background supporting the DEWs, laser and HPRF in particular, is solid. Both technologies have been known and researched for at least half a century. This has resulted in a thorough understanding of the phenomena within and around the technologies. Moreover, both technologies are in widespread use throughout the civilian and military domains. It follows that the question is not any longer about theory and concepts but about developing real life applications. It is apparent that we will witness the introduction of more DE applications in the years to come and some of these breakthroughs may benefit the developers of weapon-grade applications too.

It is evident that the DEWs are considered as potential prospects to increase future military capabilities. The money invested, the announcements given, the number of development programmes and the rise of new potential targets all speaks for the coming of DEWs. However, although some systems/technologies could be considered quite promising there are numerous issues remaining, and the history of DEWs point out that regardless of the effort and resources the obstacles may prove to be insurmountable.

Currently, we are not even close to reaching adequate power and range to engage manned aircraft size targets, and this may remain a fact for a long time. Nonetheless, the current demonstrators do seem promising in countering small UAS, and this will likely be the primary task for the first operational systems.

The insight gained through the literature review provides a good foundation for proceeding to following steps of this research and enables to compose valid and concise questionnaires for the Delphi rounds.

4. APPLICATION OF RESEARCH METHODS

“Measure what is measurable, and make measurable what is not so.”

Galileo Galilei (1564-1642)

In this chapter, the selected research methods are applied to answer SQ2: ‘What is the maturity level of GBAD DEW in 2025-2030?’ Before application each method it is first described, and the actual steps taken are explained in detail. This adds detail into the general scientific introduction of the methodology chapter and enables one to perform the tests again if necessary.

4.1. The Delphi Rounds

The implementation of the Delphi method was initiated by identifying possible participants for the panel. The idea was to have subject matter experts (SME) from three separate groups representing the scientific community, military professionals and defence industry. The goal was to have ten SMEs of each group, a total of 30 panellists. Based on the grouping the original intention was to identify possible differences in the replies of each group. This was thought to increase the validity of the results especially if significant deviation between the groups would be present.

The SME identification process was performed using several methods. Firstly an exhaustive search was made utilising several different search engines to find papers concerning DEW. This method was used to pinpoint especially the representatives of the scientific community. The authors were then contacted via email and asked to participate in the panel. In addition, an attempt was made to find Academia representatives by contacting the experts interviewed or mentioned in the articles and papers on DEW. In total 15 authors, researchers and scientists were asked to participate. Out of that, only four replied and none was able to participate.

Simultaneously the industry participants were sought by using both thesis supervisor’s and the author’s contacts. It was evident from the beginning that without correct contacts the defence industry would be difficult to reach. A total of 12 people in 10 companies were contacted. Based on publicly available sources, all the companies had an ongoing DEW- programme of their own. The majority of the contacts did not reply at all and the rest mainly rejected due to classification issues. However, four industry representatives agreed to participate.

Lastly, a number of military SMEs were contacted, some directly and some via Finnish Defence Attachés, and asked to participate. Mainly the same classification issues were given as a reason why so many military researchers declined from participating. However, a total of five military SMEs agreed to participate.

The original idea of having active military officers represented in the study was disregarded as it was considered that they would mostly view the matter from an end users perspective. This decision was based on the fact that the deployment and operation of DEW effector are not part of the problem space for this study. This decision did not however, mean, that all officers would be excluded from the panel but that they would have to possess adequate knowledge of the maturity issues of DEW. As it is stated in Chapter 2.2, Delphi is not a poll; it is a process of aggregating SME opinions.

In conclusion, the total number of panellist was 14 representing five different countries. Five of them were industry representatives, four military officers and five civil servants of armed forces. A total of 34 people were asked to participate leaving the success rate at 41%. Two main causes for such a low percentage were identified. Firstly the topic is extremely delicate, and various export restrictions and classification issues prevented the SMEs from participating. Secondly, the companies and the researchers are extremely busy professionals, and if there is nothing to be gained from their side, it is easy to turn down a request. Some even replied they would not participate unless a compensation were paid.

On a further note, there was little to do to increase the number of panellists as practically all of the identified SMEs had been asked to participate. It was realised that an attempt was needed to identify more SMEs, but this was not possible as the numbers were limited. Furthermore, it was decided to retain in the originally defined SMEs and not to include a more general population such as military officers. After all Delphi's validity is not based on the number of panellists but their expertise. The demographics of the panel is illustrated in Table 6.

Nationality	Industry	Officer/ military	Civil servant/ military
FIN	1	1	2
FRA			1
GBR	1		
NOR		3	1
SUI	1		1
USA	2		
Total	5	4	5

Table 6: Demographics of the Delphi Panel.

To make the panellists' answering as painless as possible and to ease the burden of managing the data all the questionnaires were made using a software called Facilitate Pro. The software enables to design and manage queries as well as export statics in different formats. The user's view of the first round is presented in Figure 15. It was considered necessary to provide a query which could be answered anywhere and anytime. An online query was thought to lower the threshold for answering and thus keeping the dropout rate low.

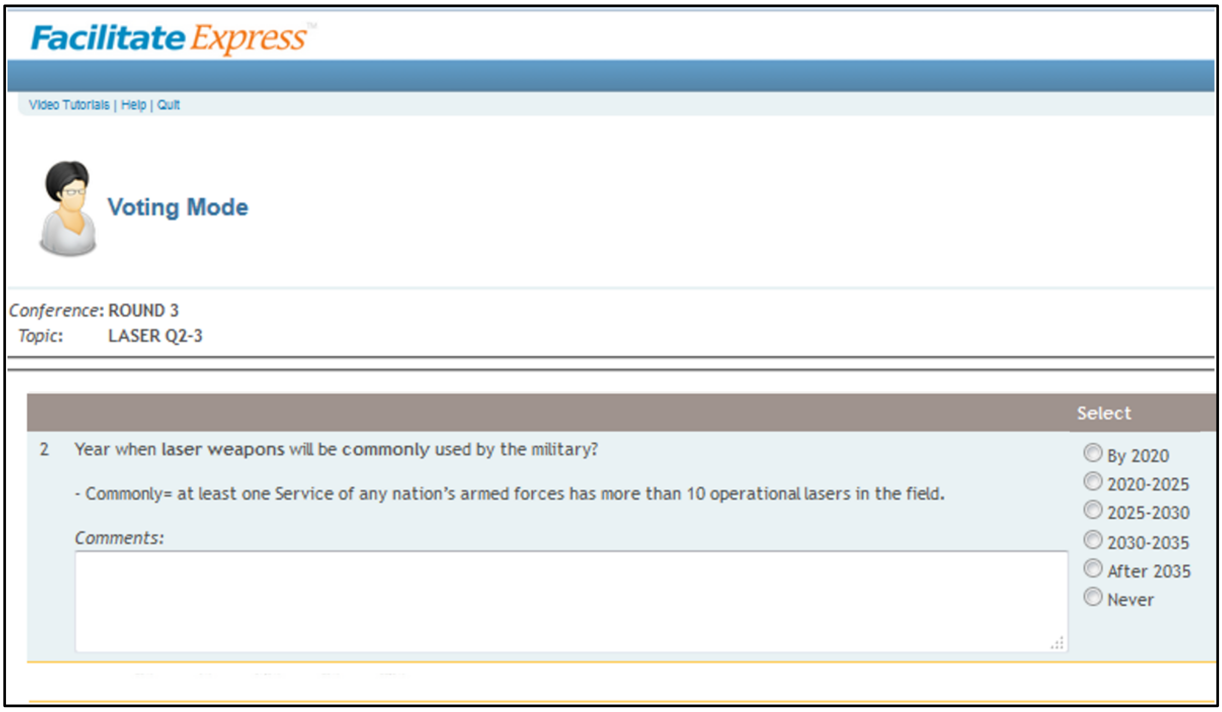


Figure 15: User View of FacilitatePro.

The Delphi process was designed as a whole keeping focus on answering the SQ2. The design process is depicted in Figure 16 below.

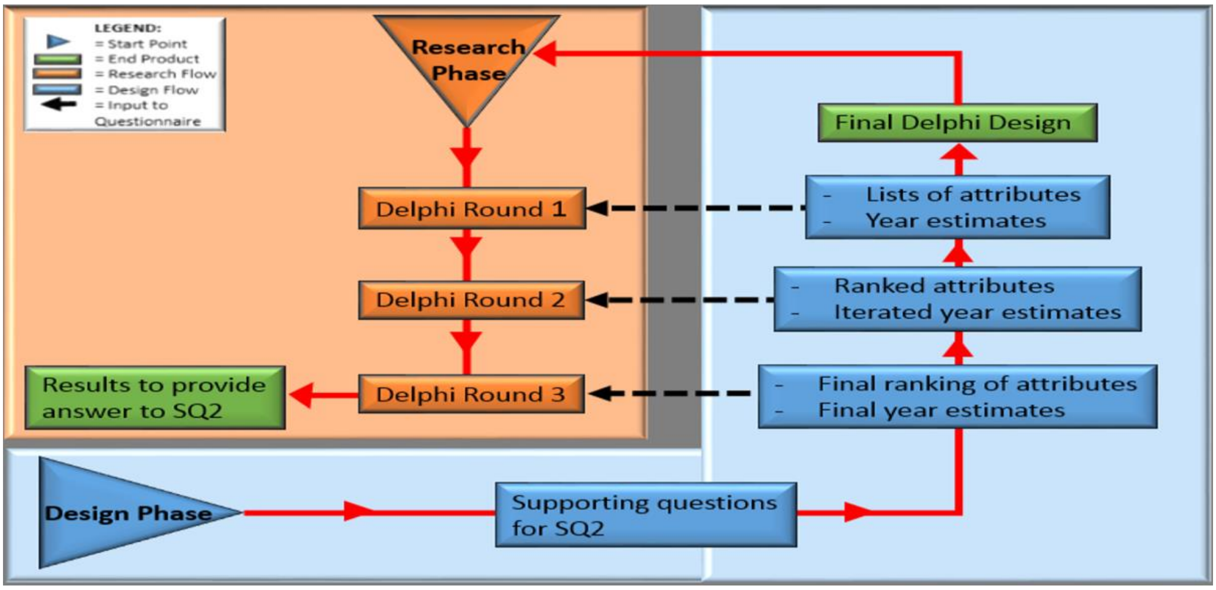


Figure 16: Design Process of Delphi Rounds in this Research.

In the picture, the design phase is illustrated in blue consisting the stages and the required products provided by each Delphi round. The design of the Delphi was performed utilising a top-down approach where the first step was to establish supporting questions for sub-question 2: ‘What is the maturity level of GBAD DEW in 2025-2030?’ This was because it was determined that the Delphi question rounds should be more comprehensive than the mere question of whether DEWs are mature in 2030. To support the sub-question 2 the following supporting questions were composed:

- What is the availability of GBAD DEW in 2030?
- What are the DEW technologies/systems available in 2030?
- What are the possible technological bottlenecks preventing DEW proliferation?
- What are the non-technical issues that may prevent DEW proliferation?

Based on the supporting questions a conclusion of round three products were made. From these products the outcomes of rounds two and one were derived which then led to the final design of the Delphi and the questionnaires, illustrated in orange, to be implemented in this research.

To apply Delphi method properly, it is vital the previous rounds provide answers that can be, after analysis and possible clustering, used in the latter rounds as the baseline. As for this research, the goal of the first round was to provide three lists of attributes identified by the panellists and four sets of year estimates to be processed in the later rounds. In rounds two and three, the lists would be ranked (ranking type Delphi) and a consensus sought regarding the year estimates (forecast Delphi). The iteration of the lists was decided to be continued until one of the four stopping criteria would be met:

1. Kendall’s W reaches 0.7 (Ranking questions). Meeting this criterion means there is a strong agreement among respondents and thus there is no need to continue iteration.
2. Results of two successive rounds show no significant change. This means that the respondents are not likely to change their answers any longer and further iteration would be a waste of time.
3. Dropout rate exceeds 40%. Higher dropout rate will compromise the validity of the results which would make continuing the iteration meaningless.
4. We reach round three. Due to the strict deadline of the research, there would not be enough time for further iterations, and the analysis must be based on three rounds.

4.2. Round One of the Delphi Panel

As said, the first question round of Delphi was designed to provide data for further iteration. The questions are shown in Table 7. The results of the open questions were clustered and sorted in alphabetical order to be used in the second round. A vague answer was first interpreted and then sent to the panellist to either confirm or rephrase. This is an important step to assure validity in the upcoming stages; only unequivocal lists should be sent for the iteration process as any speculation may interfere with the result. All the comments made by the panellists were collated in a matrix for possible future analysis.

Questions	**Remarks**
Q1: Year when laser weapons will be commonly used by the military?	Commonly= at least one Service of any nation's armed forces has more than 10 operational lasers in the field.
Q2: List **technical factors** that currently influence **laser** weapons' maturity. Justify briefly (1-2 sentences) each of your answers.	These factors can be either advancing or hindering the maturity. Include all factors regardless of their significance. Please be as specific as you can and avoid ambiguous answers e.g. "availability of components". Instead, if possible, name the component you are referring to.
Q3: Year when land based laser weapons are mature enough to be used for air defence?	Consider specifically the ability of destroying fast moving manned aircraft size targets. NOT low power non-lethal engagements (e.g. sensor dazzlement).
Q4: Year when HPRF weapons will be used by the military?	
Q5: List relevant **technical factors** that currently influence **HPRF** weapons' maturity. Justify briefly (1-2 sentences) each of your answers.	These factors can be either advancing or hindering the maturity. Include all factors regardless of their significance. Please be as specific as you can and avoid ambiguous answers e.g. "availability of components". Instead, if possible, name the component you are referring to.
Q6: Year when land based HPRF weapons are mature enough to be used for air defence?	Consider a situation where an airborne platform is **forced to abort** its mission after a being engaged by HPRF weapon.
Q7: List relevant **non-technical** factors that influence/could have an impact on **the proliferation of DEW.** Justify briefly (1-2 sentences) each of your answers.	These factors can be either advancing or hindering the proliferation. Include all factors regardless of their significance. In this question "non-technical" refers to reasons of e.g. political, tactical, cultural, budgetary nature.

Table 7: Round One Questions and Remarks.

In total the first round consisted seven questions of which three were related to a year and four to features related to DEW maturity. It was regarded vital to include definitions to some of the otherwise ambiguous terms such as 'commonly' or 'in use for air defence'. It was seen very likely the panellists would have defined these terms individually and there would have been problems in interpreting the answers and in some cases, these problems could have proved to be insurmountable thus shattering the basis of the complete research. For instance, the validity of the answers to question three would have been somewhat questionable if all answers would have been given based on personal definitions. Furthermore, this would have made the Delphi iteration impossible as the panellists had answered to different questions.

It should be noted, however, that the definitions given could have also been different. This is to say that before sending the first questionnaire a decision had to be made regarding the definitions. Let us look more in depth for question one as an example. There are an almost infinite number of other legitimate definitions for ‘commonly’. Obviously, there are also some that are illegitimate due to absurdity too but let us focus on the legitimate ones. One could have inserted any number instead of ten as the number of operational systems. For example, 9 or 11 would have been just as good as 10 and most likely would have returned the same answers. On the other hand, however, 21 or 71 could have altered the answers. For this study 10 was selected, not only because it is a nice even number, but foremostly because it was considered to express a ‘common enough’ employment especially when it was also stated that all the systems should be in use by single Armed Service. As was said 9 and 11 would have returned the same answers but on the other hand, 3 or 4 were considered too small numbers to describe common use. For this study, three ships equipped with lasers is not common use. On the other hand, if the number of systems in use would have been defined to be significantly more than ten, 50 for example, was considered to indicate a somewhat widespread use.

As stated in the literature review, DEWs encompass several levels of use. For lasers, these levels range from dazzling of sensors/operators to destruction of the vehicle and for HPRF from upsetting the target’s electronics to physical destruction of targets components. Due to these tiers it seemed likely, there would be confusion regarding what is asked. If one is asked ‘Can X be done?’ the answer might be positive but if he is asked ‘Can X be done with 100 euros and within one hour?’ one could get an opposing answer. To mitigate this ambiguity a set of scenario-like definitions were created.

It was decided to define ‘use of laser in air defence’ as the system’s capability to destroy fast moving manned aircraft size targets and ‘use of HPRF in air defence’ as the system’s capability to force an airborne target to abort its mission. The decision was based on the fact that this research is specifically focused on the GBAD applications of DEW as a whole without a specific area in mind (e.g. CRAM or counter-UAV). By introducing these ‘scenarios’ the questionnaire and the questions within were made as explicit as possible.

Answers to Q1

Answers and their deviation for question 1: *’Year when laser weapons will be commonly used by the military?’* are shown in the following diagram.

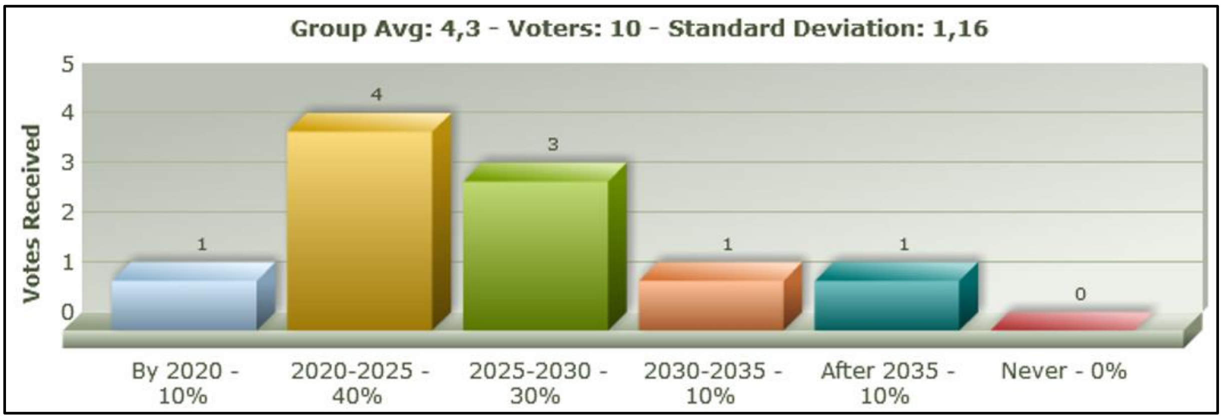


Figure 17: Round 1 Q1 Answers.

Answers to Q2

The answers for Q2: *‘List technical factors that currently influence laser weapons’ maturity’* are shown in Table 8. A total of 28 factors were pointed out of which three were regarded as advancing and the rest 25 as challenges to be solved. These answers were clustered to remove duplicates and to provide a concise alphabetical list of factors to be rated in round 2. The clustered list is presented in Table 9.

Advancing factors	Hindering factors
Computer power, increased computing power solves some of the challenges with laser	Necessity for lengthy vulnerability studies in order to know if some applications are interesting or not
Industrial laser development	Pump laser power and weight
Duality particularly for fibre laser	Cooling requirements/wall plug efficiency
	Precision tracking for range performance
	High power single mode lasers
	Demanding power consumption
	Raman scattering in sinle mode fiber
	Collateral damage
	Power consumption
	Blooming
	Tracking capability
	Sufficient output level
	Energy efficiency
	Handling of cehimcals in chemical lasers
	Costly
	Size and power
	Beam quality
	Adaptive optics and beam combining
	Robustiness
	Wall plug efficiency
	Waste Heat
	Size and mobility issues related to high power demand
	Availability of necessary portable power
	Cooling
	Testing facilities and testing rules

Table 8: Round 1 Q2 Answers.

Advancing Factors	Hindering Factors
Computer power, increased computing power solves some of the challenges with laser	Adapive optics and beam combining
Industrial laser development	Beam quality (Raman scattering, blooming)
	Buyers' hesitation to order/invest
	Collateral damage
	Cooling/Waste heat
	Cost
	Handling of chemicals in chemical lasers
	Mobility
	Necessity for lengthy vulnerability studies in order to know if some applications are interesting or not
	Power consumption
	Precision tracking for range performance
	Robustness
	Size
	Sufficient output level
	Testing facilities and testing rules
	Wall plug efficiency

Table 9: Round 1 Q2 Answers Clustered.

Answers to Q3

Answers and their deviation for question 3: *'Year when land based laser weapons are mature enough to be used for air defence?'* are shown in the following diagram.

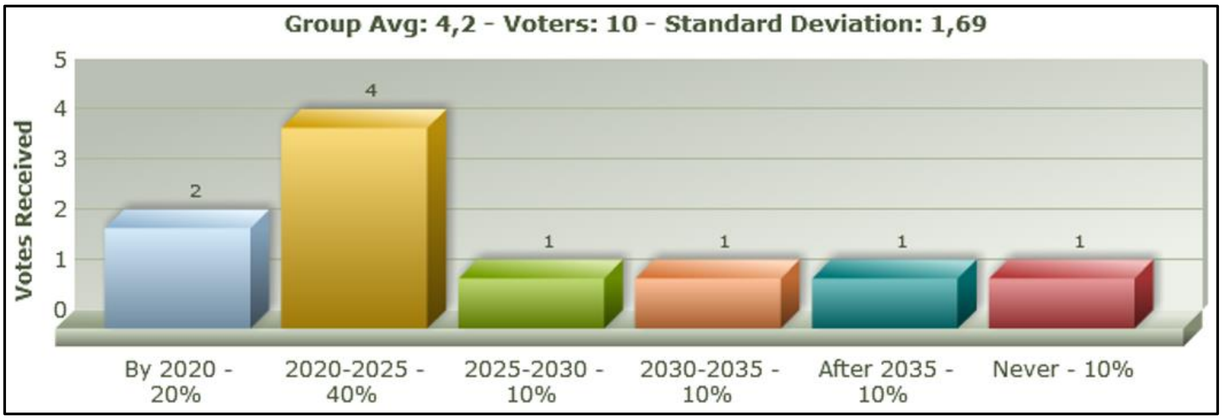


Figure 18: Round 1 Q3 Answers.

Answers to Q4

Answers and their deviation for question 4: *'Year when HPRF weapons will be used by the military?'* are shown in the following diagram.

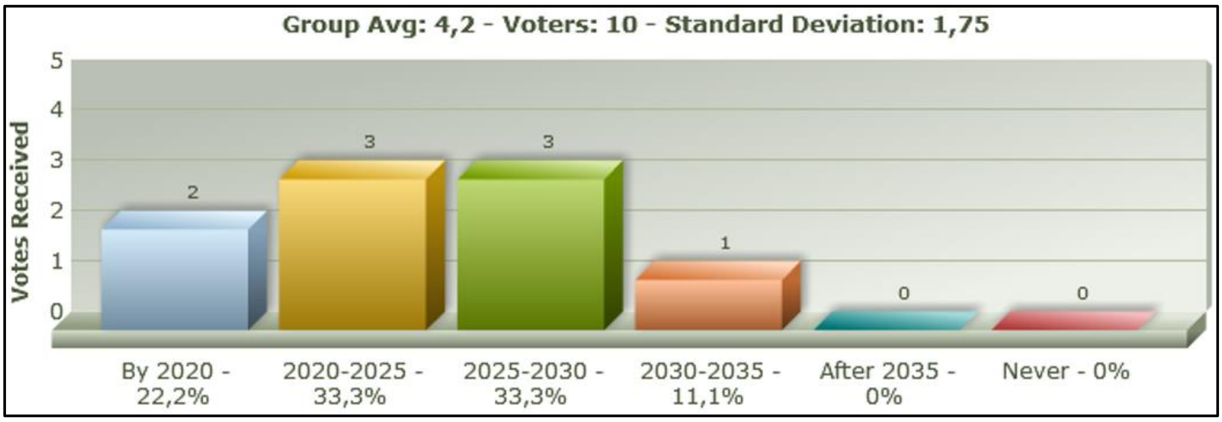


Figure 19: Round 1 Q4 Answers.

Answers to Q5

The answers for Q5: *'List relevant technical factors that currently influence HPRF weapons' maturity'* are shown in Table 10. A total of 18 factors were pointed out of which 4 were regarded as advancing and the rest 14 as challenges to be solved. These answers were clustered to remove duplicates and to provide a concise alphabetical list of factors to be rated in round 2. The clustered list is presented in Table 11.

Advancing factors	Hindering factors
Duality : Radar / Telecom.	Lack of directionality results in poor range performance.
Development of Solid state device (amplifier)	Demanding power consumption
Relative simplicity compared to laser	EM Compatibily with the platform
Relatively cheaper than laser	Power
	Frequency/wavelength
	Modulation
	Engagement angle
	Computing capability
	Power
	Antenna
	Size (portability)
	Reliability
	Beam directing
	Power generation

Table 10: Round 1 Q5 Answers.

Advancing factors	Hindering factors
Duality : Radar / Telecom.	Antenna
Development of Solid state device (amplifier)	Buyers' hesitation to order/invest
Relative simplicity compared to laser	Computing capability
Relatively cheaper than laser	Demanding power consumption
	EM Compatibility with the platform
	Engagement angle
	Frequency/wavelength
	Lack of directionality
	Modulation
	Power
	Reliability
	Size

Table 11: Round 1 Q5 Answers Clustered.

Answers to Q6

Answers and their deviation for question 6: *'Year when land based HPRF weapons are mature enough to be used for air defence?'* are shown in the following diagram.

Figure 20: Round 1 Q6 Answers

Answers to Q7

The answers for Q7: *'List relevant non-technical factors that influence/could have an impact on the proliferation of DEW'* are shown in Table 12. A total of 21 factors were identified by the SME's. All of these were issues that could hinder the maturation of technology or the widespread use of the technology. These answers were clustered to remove duplicates and to provide a concise alphabetical list of factors to be rated in round 2. The clustered list consisting 15 attributes is presented in Table 13.

Non-technical factors
Access to high power single mode lasers could limit proliferation due to the high cost of development
Airspace control
Blinding / collateral damage is widely used as a problem with laser weapons , politically a difficult choice to make
Civilian technology's (gps, wifi, mobile networks, ...) vulnerability to HPRF weapons
Collateral damage
Collateral eye damage may happen if the target is highly refelective. There are no laws how to use laser weapons.
Fratricide and collateral damage behind target
Health and safety concerns for operators
High cost
Laser and HPM Legislation, HERP standards
Operational concepts underpinning a safe and secure way of using it
Operational principles: even if the technology will be mature, the way to do defence is related to tradition
Possible extension of the Geneva protocol on blinding lasers
Reflection of laser light from target/other objects can be a severe health problem (eyes)
Robustiness. Higly technival devices have some mean time between failure. The length of MTBF will strongly affect the user experience
Rules of Engagement for these weapons are needed
The moral aspect as a hinder: An impression amongst the public that DEW are immoral/dirty weapons that may target or injure innocent people, or that they may cause unnecessary pain.
Use of chemicals and control of it
Weather. Clouds, rain etc.
Legislation and subsequent RoE's for the safe use
Acceptabilty by the Military community

Table 12: Round 1 Q7 Answers.

Non-technical factors
Acceptability by the Military community: even if the technology would be mature, the way to do defence is related to tradition
Access to high power single mode lasers could limit proliferation due to the high cost of development
Airspace control
Civilian technology's (gps, wifi, mobile networks, ...)vulnerability to HPRF weapons
Fratricide and collateral damage behind target
Health and safety concerns for operators
High cost
Legislation
Operational concepts underpinning a safe and secure way of using it
Possible extension of the Geneva protocol on blinding lasers
Robustiness. Higly technival devices have some mean time between failure. The length of MTBF will strongly affect the user experience
Rules of Engagement
The moral aspect as a hinder: An impression amongst the public that DEW are immoral/dirty weapons that may target or injure innocent people, or that they may cause unnecessary pain.
Use of chemicals and control of it
Weather. Clouds, rain etc.

Table 13: Round 1 Q7 Answers Clustered.

4.2.1. Summary of Round One

A total of 10 respondents provided answers for round one. The goal of the round was achieved and the answers enabled to proceed to the next round. There was, however, an observation made that possibly not all the panellists had noted the definitions or mini-scenarios while considering their answers. This observation was based on the illogicality in answers to questions 1 and 3. It was observed that the results of questions 1 and 3 were unexpectedly stating that laser air defence applications against manned size targets would be in use at the same time or even sooner than lasers in general. Based on the literature review this was thought to have been quite the opposite as many papers state there are still many problems in effectively engaging manned aircraft in the near future whereas many laser weapons, although low power, are already in use or demonstrator phase. Two reasons for this were identified.

Firstly the answers could be correct, and there were unprecedented factors that would require further research. One such factor identified was that the panellists would regard the non-technical factors in Q7 so influential that they will prevent the proliferation although the technology would be mature enough. A decision was made that if this would be the case, then it would be investigated during round 2 analysis and addressed in round 3 questions.

On the other hand, the answers could have been given without considering the definitions explained in the ‘Remarks’ column. The latter explanation was deemed to be more likely, and this was also supported by some of the free text answers provided. It was decided to emphasise the definitions in the upcoming rounds and monitor the answers to see if the phenomenon would persist. Nonetheless, the Delphi iteration should either remove the problem or make it even more prominent in the later rounds.

4.3. Round Two of the Delphi Panel

Based on the round one answers the round two questionnaire consisted the same three timeline assessment questions together with four lists of attributes to be ranked. An emphasis was made to highlight the important definitions for the panellist to minimise interpretation issues. The questionnaire also included a free text column, and the respondents were encouraged to justify their calls and comment the topics in general. The questions of Round 2 are illustrated in Table 14.

The questionnaire was sent to all ten panellists who replied to round one. They were given two weeks to respond after which a reminder was sent to those who had not replied. A total of three reminders were sent and the total answering time was approximately eight weeks. Nevertheless, only eight answers were received. Furthermore, not all replied to all questions, based on their lack of expertise in particular areas, meaning the number of replies was in some cases as low as 7. This led to the fact that the dropout rate exceeded the value of the termination criterion three: 'Dropout rate is 40% or higher'. This is further discussed in the summary of Round 2.

Questions	Remarks
Q1: Rank the following factors **advancing laser weapon maturity** in order of significance. 1 = Most significant, 2 = least significant. If you feel the list is missing factor/s, please add them in "Remarks" column.	Before answering take a look at the results of Round 2. Give EACH attribute a ranking. No two attribute can be ranked equal. You are encouraged to justify your ranking in the "Remarks" column, especially regarding the most/least significant factors.
Q2: Rank the following factors **hindering laser weapon maturity** in order of significance. 1 = Most significant, 16 = least significant. If you feel the list is missing factor/s, please add them in "Remarks" column.	Before answering take a look at the results of Round 2. Give EACH attribute a ranking. No two attribute can be ranked equal. You are encouraged to justify your ranking in the "Remarks" column, especially regarding the most/least significant factors.
Q3: Year when **laser weapons** will be **commonly** used by the military?	Before answering take a look at the results of Round 1 and keep in mind the lists of factors you just ranked. NOTE: Consider the relation between questions 3&4 together keeping in mind the descriptions under the questions. - **Commonly**= at least one Service of any nation's armed forces has more than 10 operational lasers in the field.
Q4: Year when **land based** laser weapons are mature enough to be used **for air defence**?	Before answering take a look at the results of Round 1 and keep in mind the lists of factors you just ranked. NOTE: Consider the relation between questions 3&4 together keeping in mind the descriptions under the questions. - Consider the ability of **destroying fast moving manned aircraft size targets**. NOT low power non-lethal engagements (e.g. sensor dazzlement).
Q5: Rank the following factors **advancing HPRF weapon maturity** in order of significance. 1 = Most significant, 4 = least significant	Give EACH attribute a ranking. No two attribute can be ranked equal. You are encouraged to justify your ranking in the "Remarks" column, especially regarding the most/least significant factors.
Q6: Rank the following factors **hindering HPRF weapon maturity** in order of significance. 1 = Most significant, 11 = least significant	Give EACH attribute a ranking. No two attribute can be ranked equal. You are encouraged to justify your ranking in the "Remarks" column, especially regarding the most/least significant factors.
Q7: Year when **HPRF weapons** are **commonly** used by the military?	Before answering take a look at the results of Round 1 and keep in mind the lists of factors you just ranked. - **Commonly=** at least one Service of any nation's armed forces has more than 10 operational HPRF weapons in the field.
Q8: Year when land based **HPRF weapons** are mature enough to be used **for air defence**?	Before answering take a look at the results of Round 1 and keep in mind the lists of factors you just ranked. - Consider a situation where an airborne platform is **forced to abort** its mission after being engaged by HPRF weapon.
Q9: Rank the following *non-technical factors that influence/could have an impact on the proliferation of DEW* in order of significance. 1 = Most significant, 15 = least significant	Give EACH attribute a ranking. No two attribute can be ranked equal. You are encouraged to justify your ranking in the "Remarks" column, especially regarding the most/least significant factors.

Table 14: Round 2 Questions.

Answers to Q1

In Q1 of Round 2, the panellists were given two factors, based on Q2 of Round 1, to be ranked. The answers for Q1: *'Rank the following factors advancing laser weapon maturity in order of significance'* are depicted in the table below.

Panellists	Computer power, increased computing power solves some of the challenges with laser	Industrial laser development
0JV	1	2
39U	1	2
6XA	1	2
9GC	2	1
CWU	1	2
F9C	1	2
GO1	1	2
HP2	1	2

Table 15: Round 2 Q1 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.5625$

$X^2 = 4.5$

p-value= 0.034.

Answers to Q2

In Q2 of Round 2, the panellists were given 16 factors, based on Q2 of Round 1, to be ranked. The answers for Q2: *'Rank the following factors hindering laser weapon maturity in order of significance'* are depicted in the table below.

Panellists	Adapive optics and beam combining	Beam quality (Raman scattering, blooming)	Buyers' hesitation to order/invest	Collateral damage	Cooling/Waste heat	Cost	Handling of chemicals in chemical lasers	Mobility	Necessity for lengthy vulnerability studies	Power consumption	Precision tracking for range performance	Robustness	Size	Sufficient output level	Testing facilities and testing rules	Wall plug efficiency
0JV	14	15	2	1	4	3	5	13	6	12	11	7	8	16	9	10
39U	11	15	10	16	3	7	2	6	5	12	14	9	8	13	4	1
6XA	5	6	11	1	14	13	15	9	10	16	8	4	3	12	7	2
CWU	11	12	13	14	4	10	1	5	7	6	16	8	3	15	9	2
F9C	7	8	2	16	13	3	6	4	1	11	12	14	5	10	15	9
GO1	15	16	14	3	13	2	1	12	9	10	11	8	7	6	5	4
HP2	10	9	11	1	14	12	7	2	6	16	4	5	13	15	3	8

Table 16: Round 2 Q2 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.2412$

$X^2 = 25.32$

p-value= 0.046.

Based on the answers a table, depicted below in Table 17, consisting the ranked attributes was composed.

	Mean Rank	Rank
Wall plug efficiency	5,14	1
Handling of chemicals in chemical lasers	5,29	2
Necessity for lengthy vulnerability studies	6,29	3
Size	6,71	4
Cost	7,14	5
Mobility	7,29	6
Collateral damage	7,43	7
Testing facilities and testing rules	7,43	8
Robustness	7,86	9
Buyers' hesitation to order/invest	9,00	10
Cooling/Waste heat	9,29	11
Adapive optics and beam combining	10,43	12
Precision tracking for range performance	10,86	13
Beam quality (Raman scattering, blooming)	11,57	14
Power consumption	11,86	15
Sufficient output level	12,43	16

Table 17: Ranking based on Round 2 Q2 Answers.

Answers to Q3

The answers for Q3: *'Year when laser weapons will be commonly used by the military?'* are depicted in the diagram below.

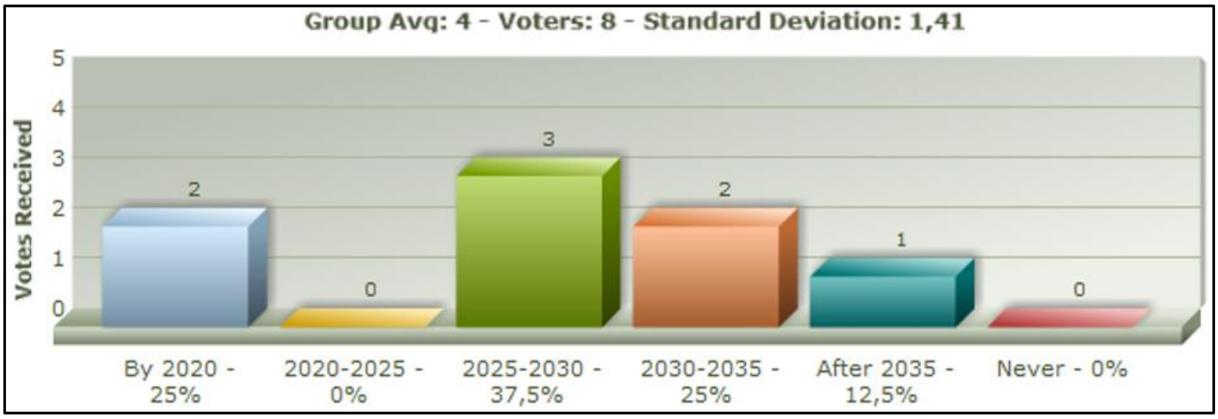


Figure 21: Round 2 Q3 Answers.

Answers to Q4

The answers for Q4: *'Year when land based laser weapons are mature enough to be used for air defence?'* are depicted in the diagram below.

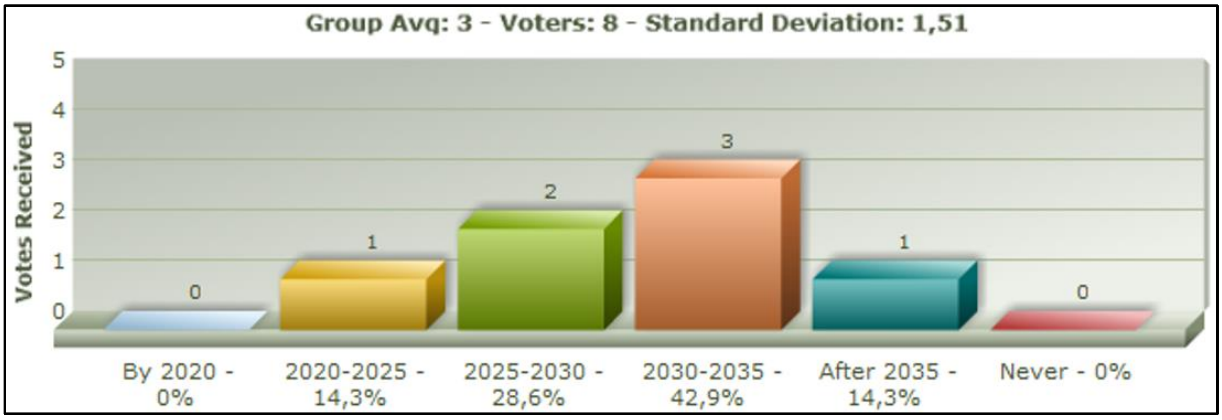


Figure 22: Round 2 Q4 Answers.

Answers to Q5

In Q5 of Round 2, the panellists were given four factors, based on Q5 of Round 1, to be ranked. The answers for Q5: *'Rank the following factors advancing HPRF weapon maturity in order of significance'* are depicted in the table below.

Panellists	Duality : Radar / Telecom.	Development of Solid state device (amplifier)	Relative simplicity compared to laser	Relatively cheaper than laser
39U	1	2	4	3
6XA	2	1	3	4
9GC	4	3	2	1
CWU	3	4	2	1
F9C	3	2	4	1
GO1	3	4	2	1
HP2	1	4	2	3

Table 18: Round 2 Q5 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.086$

$X^2 = 1.8$

p-value= 0.615.

Based on the answers a table, depicted below in Table 19, consisting the ranked attributes was composed.

	Mean Rank	Rank
Relatively cheaper than laser	2	1
Duality : Radar / Telecom.	2,43	2
Relative simplicity compared to laser	2,71	3
Development of Solid state device (amplifier)	2,86	4

Table 19: Ranking based on Round 2 Q5 Answers.

Answers to Q6

In Q6 of Round 2, the panellists were given 11 factors, based on Q5 of Round 1, to be ranked. The answers for Q6: *'Rank the following factors hindering HPRF weapon maturity in order of significance'* are depicted in the table below.

Panellists	Antenna	Buyers' hesitation to order/invest	Computing capability	Demanding power consumption	EM Compatibility with the platform	Frequency/wavelength	Lack of directionality	Modulation	Power	Reliability	Size
39U	5	11	7	2	3	4	9	10	8	1	6
6XA	2	4	3	5	6	7	8	9	1	11	10
9GC	7	11	9	6	10	4	2	1	3	5	8
CWU	11	10	1	8	9	6	7	2	4	3	5
F9C	4	11	8	3	10	9	6	5	2	7	1
GO1	6	9	10	4	7	8	11	5	3	1	2
HP2	2	4	5	6	3	7	8	9	10	11	1

Table 20: Round 2 Q6 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.14$

$X^2 = 9.77$

p-value= 0.46.

Based on the answers a table, depicted below in Table 21, consisting the ranked attributes was composed.

	Mean Rank	Rank
Power	4,43	1
Size	4,7	2
Demanding power consumption	4,9	3
Antenna	5,29	4
Reliability	5,6	5
Modulation	5,86	6
Computing capability	6,1	7
Frequency/wavelength	6,43	8
EM Compatibility with the platform	6,86	9
Lack of directionality	7,29	10
Buyers' hesitation to order/invest	8,57	11

Table 21: Ranking based on Round 2 Q6 Answers.

Answers to Q7

The answers for Q7: *'Year when HPRF weapons are commonly used by the military?'* are depicted in the diagram below.

Figure 23: Round 2 Q7 Answers.

Answers to Q8

The answers for Q8: *'Year when land based HPRF weapons are mature enough to be used for air defence?'* are depicted in the diagram below.

Figure 24: Round 2 Q8 Answers.

Answers to Q9

In Q9 of Round 2, the panellists were given 15 factors, based on Q7 of Round 1, to be ranked. The answers for Q9: *'Rank the following non-technical factors that influence/could have an impact on the proliferation of DEW in order of significance'* are depicted in the table below. Based on the statistical method applied the answers of one panellist were excluded as he had not ranked all factors. The inclusion of his rankings could have distorted the answers and thus the validity of the research.

Panellists	Acceptability by the Military community: even if the technology would be mature, the way to do defence is related to	Access to high power single mode lasers could limit proliferation	Airspace control	Civilian technology's (gps, wifi, mobile networks, ...) vulnerability to HPRF weapons	Fratricide and collateral damage behind target	Health and safety concerns for operators	High cost	Legislation	Operational concepts underpinning a safe and secure way of using it	Possible extension of the Geneva protocol	Robustness. Higly technival devices have some mean time between failure. The length of MTBF will strongly affect the user experience	Rules of Engagement	The moral aspect as a hinder: An impression amongst the public that DEW are immoral/dirty weapons that may target or injure innocent people, or that they may	Use of chemicals and control of it	Weather. Clouds, rain etc.
39U	1	7	13	8	14	3	11	6	10	5	9	12	2	4	15
6XA	3	9	1	8	7	6	10	15	2	14	4	13	5	12	11
9GC	3	6	4	2	13	15	10	14	8	12	7	5	9	1	11
CWU	3	15	9	13	10	8	7	6	14	4	5	11	2	1	12
F9C	6	2	10	4	11	15	1	7	5	14	9	13	12	3	8
GO1	15	6	1	11	5	10	13	4	12	3	9	7	2	8	14

Table 22: Round 2 Q9 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.2$

$X^2 = 16.87$

p -value= 0.26

Based on the answers a table, depicted below in Table 23, consisting the ranked attributes was composed.

	Mean Rank	Rank
Use of chemicals and control of it	5	1
Acceptability by the Military community: even if the technology would be mature, the way to do defence is related to tradition	5,17	2
The moral aspect as a hinder: An impression amongst the public that DEW are immoral/dirty weapons that may target or injure innocent people, or that they may cause unnecessary pain.	5,33	3
Airspace control	6	4
Robustness. Higly technival devices have some mean time between failure. The length of MTBF will strongly affect the user experience	7,17	5
Access to high power single mode lasers could limit proliferation due to the high cost of development	7,5	6
Civilian technology's (gps, wifi, mobile networks, ...) vulnerability to HPRF weapons	7,67	7
Operational concepts underpinning a safe and secure way of using it	8,5	8
High cost	9	9
Legislation	9	10
Possible extension of the Geneva protocol on blinding lasers	9	11
Fratricide and collateral damage behind target	10	12
Health and safety concerns for operators	10	13
Rules of Engagement	10	14
Weather. Clouds, rain etc.	12	15

Table 23: Ranking based on Round 2 Q9 Answers.

4.3.1. Summary of Round Two

Round two consisted nine questions including both attribute rankings and year estimations. The year estimations were the iteration of the same questions asked in Round 1. The rankings of factors were performed for the first time although based on the lists produced by the panellists in Round 1. Round two gave us the first opportunity to assess and analyse the answers and their validity and also to assess the overall situation regarding the stopping criteria presented in Chapter 4.1. It is significant to keep the stopping criteria in mind before composing the questionnaire for the next round because, for example, there may be some questions which do not require further iteration for one reason or another. Thus an initial analysis of the results was performed, and its results are discussed next.

Based on the stopping criteria set in chapter 4.1 the following observations were made:

1. Kendall's *W* reaches 0.7 (Ranking questions). No ranking question's *W*- value reached anywhere close to 0.7. The best value was 0.5625 which represents moderate agreement, but all other values were extremely poor, some less than 0.1, so this stopping criterion was not met. However, the results of question 1 were seen to require further analysis of their validity. This was because despite the fact that panellists had almost unanimously ranked the attributes, in the same way, *W*- value was still quite modest. Based on this observation a sensitivity analysis was performed and by deleting one panellist's rankings (9GC) gave us a *W*-value of 1 meaning full agreement. Based on this it was decided that question 1: *'Rank the following factors advancing laser weapon maturity in order of significance'* would not be included in the upcoming round as the panel had reached strong agreement although not indicated by the *W*- value.

2. Results of two successive rounds show no significant change. This criterion was not present in any of the questions. All the classic Delphi results showed change towards a more unified result. In addition, the ranking questions had no previous round to compare with. The changes in the results of the classic Delphi questions are shown in the following diagrams, and they all represent a clear shift towards a more consolidated result. As the iteration process was not finished these results were not scrutinised any further at this phase.

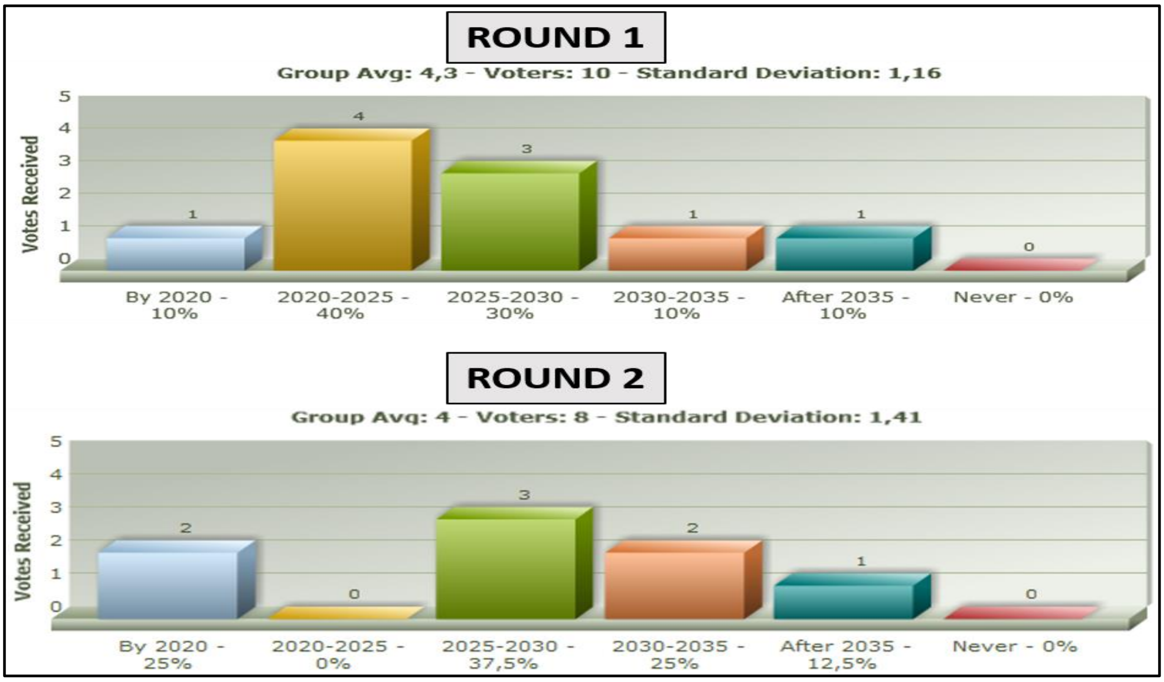


Figure 25: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when laser weapons will be commonly used by the military?*

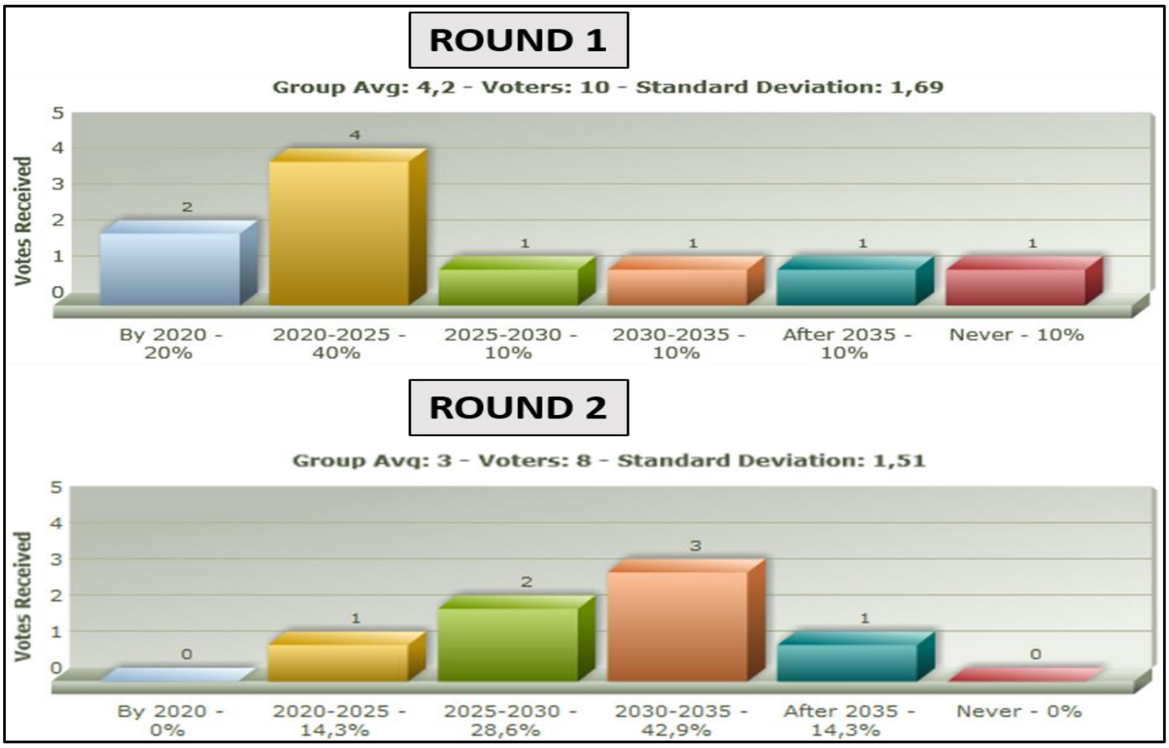


Figure 26: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when land based laser weapons are mature enough to be used for air defence?*

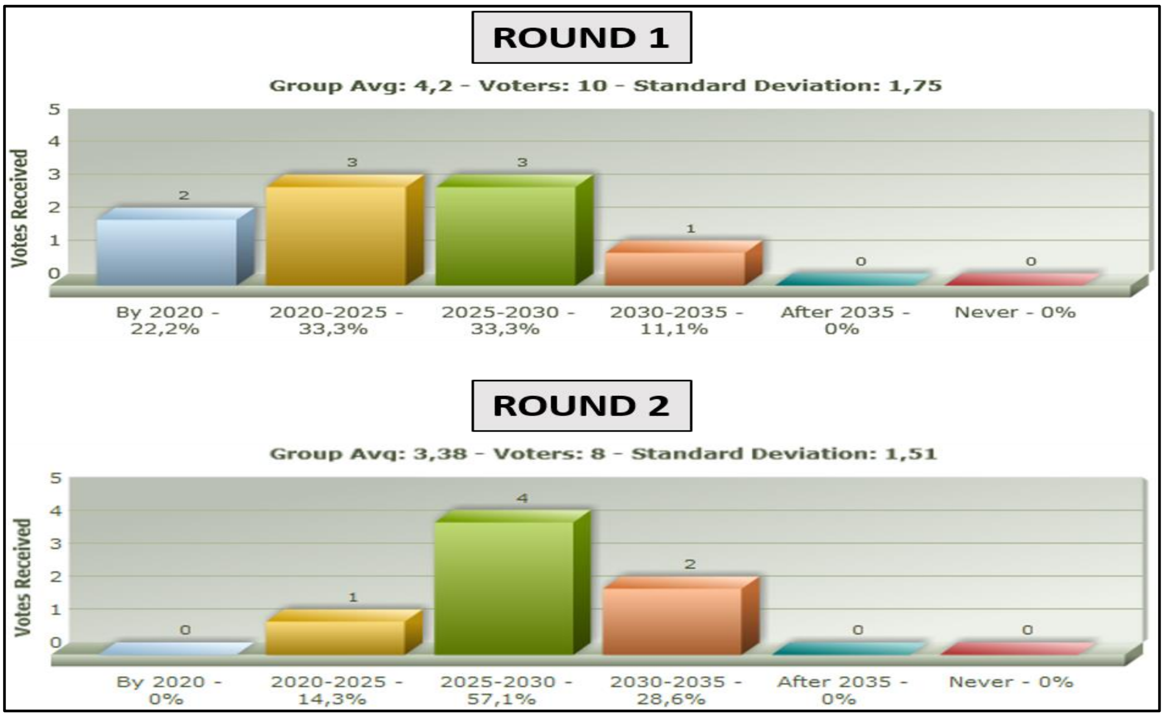


Figure 27: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when HPRF weapons will be used by the military?*

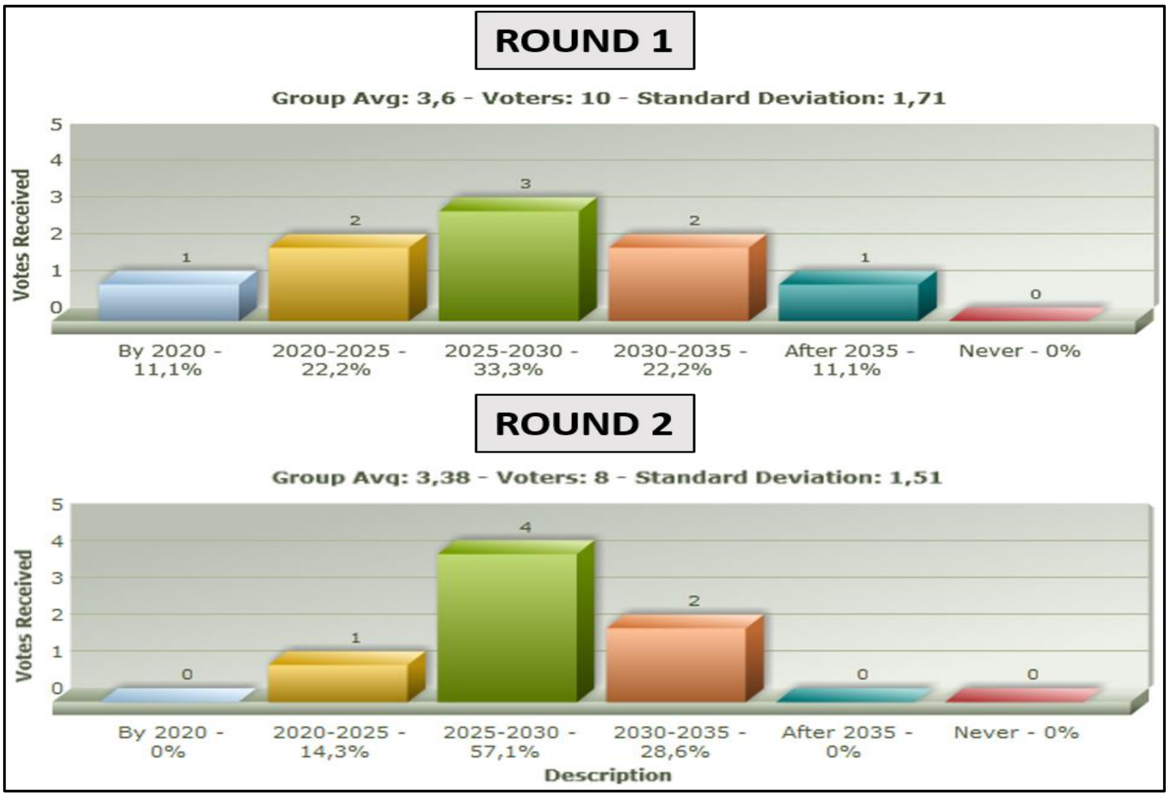


Figure 28: Evolvement of Replies between Rounds 1 and 2 to Question: *Year when land based HPRF weapons are mature enough to be used for air defence?'*

3. Dropout rate exceeds 40%. Whether or not this stopping criterion was met depends on the approach. When the stopping criteria were set, it was not decided what the comparison number is, and thus there are two ways of looking at the criterion. The first view on the issue is to regard the number of people who agreed to answer (13) as the comparison value. This would mean that since the number of respondents in round two was between six and eight the dropout rate would range from 38.5% (n=8) to 53.9% (n=6). This approach means that all questions with n<8 meet this stopping criterion. As a result questions 2, 5, 6 and 9 would not be eligible for further iteration.

   Another approach is to consider the number of actual respondents in round one (10) as the comparison value. Should this be the case, we would get dropout rates ranging from 20% (n=8) to 40% (n=6). If this approach is applied none of the questions, although question 9 sits on the threshold, would meet the stopping criterion. It was decided to adopt the latter approach as it enabled us to proceed the iteration. By choosing the other approach, we would have had to stop the iteration process and start over the panellist identification. As this research has a strict deadline, this was not possible. Furthermore, it was established that this was more to do with the equivocal stopping criterion than the validity of the research. This controversy in interpreting a stopping criterion underlines the significance of composing unambiguous stopping criteria.

4. <u>We reach round three.</u> This does not need any explanation as this was not the case at this time.

4.4. Round Three of the Delphi Panel

Based on the round two answers round three questionnaire consisted the same four timeline assessment questions and three attribute lists to be ranked. Based on round 2 results one ranking question was decided to be excluded from further iteration, the reasons behind this are discussed above in chapter 4.3.1. The panellists were made aware of the results of previous round by providing them with diagrams depicting the answer distribution and the ranks and mean ranks.

Again, as was done in round 2, an emphasis was made to highlight the definitions for the panellist to minimise interpretation issues. The questionnaire also included a free text column, and the respondents were encouraged to justify their calls and comment the topics in general. The questions of Round 3 are illustrated in Table 24.

Questions	**Remarks**
Q1: Rank the following factors **hindering laser weapon maturity** in order of significance. 1 = Most significant, 16 = least significant. If you feel the list is missing factor/s, please add them in "Remarks" column.	Before answering take a look at the results of Round 2. Give EACH attribute a ranking. No two attribute can be ranked equal.
Q2: Year when **laser weapons** will be **commonly** used by the military?	Before answering take a look at the results of Round 2 and keep in mind the lists of factors you just ranked. NOTE: Consider the relation between questions 2&3 together keeping in mind the descriptions under the questions. - Commonly= at least one Service of any nation's armed forces has more than 10 operational lasers in the field.
Q3: Year when **land based** laser weapons are mature enough to be used **for air defence?**	Before answering take a look at the results of Round 1 and keep in mind the lists of factors you just ranked. NOTE: Consider the relation between questions 2&3together keeping in mind the descriptions under the questions. - Consider the ability of **destroying fast moving manned aircraft size targets**. NOT low power non-lethal engagements (e.g. sensor dazzlement).
Q4: Rank the following factors **advancing HPRF weapon maturity** in order of significance. 1 = Most significant, 4 = least significant	Before answering take a look at the results of Round 2. Give EACH attribute a ranking. No two attribute can be ranked equal.
Q5: Rank the following factors **hindering HPRF weapon maturity** in order of significance. 1 = Most significant, 11 = least significant	Before answering take a look at the results of Round 2. Give EACH attribute a ranking. No two attribute can be ranked equal.
Q6: Year when **HPRF weapons are commonly** used by the military?	Before answering take a look at the results of Round 2 and keep in mind the lists of factors you just ranked. - **Commonly=** at least one Service of any nation's armed forces has more than 10 operational HPRF weapons in the field.
Q7: Year when land based **HPRF weapons** are mature enough to be used **for air defence?**	Before answering take a look at the results of Round 2 and keep in mind the lists of factors you just ranked. Consider a situation where an airborne platform is **forced to abort** its mission after a being engaged by HPRF weapon.
Q8: Rank the following *non-technical factors that influence/could have an impact on the proliferation of DEW* in order of significance. 1 = Most significant, 15 = least significant	Before answering take a look at the results of Round 2. Give EACH attribute a ranking. No two attribute can be ranked equal.

Table 24: Round 3 Questions.

The questionnaire was sent to all eight panellists who replied to round two. They were given two weeks to reply after which a reminder was sent to those who had not responded. A total of three reminders were sent and the total answering time was approximately ten weeks. Nonetheless, there were no dropouts in round three, and all panellists replied. However, not all replied to all questions, based on their lack of expertise in particular areas, meaning the number of replies was in some cases as low as 7.

Answers to Q1

In Q1 of Round 3, the panellists were given 15 factors, based on Q2 of Round 2, to be ranked. The answers for Q1: *'Rank the following factors hindering laser weapon maturity in order of significance'* are depicted in the table below.

Factor	Respondents							Sum of ranks	Mean rank	Rank
	9GC	39U	6XA	GO1	CWU	F9C	HP2			
Precision tracking for range performance	4	7	2	10	13	1	2	39	5,571	1
Beam quality (Raman scattering, blooming)	5	8	3	14	6	2	4	42	6,000	2
Adapive optics and beam combining	3	5	6	16	7	3	6	46	6,571	3
Power consumption	2	9	5	13	2	7	10	48	6,857	4
Cooling/Waste heat	7	4	7	11	4	12	5	50	7,143	5
Buyers' hesitation to order/invest	6	11	1	12	5	8	7	50	7,143	6
Sufficient output level	1	6	4	15	11	6	11	54	7,714	7
Mobility	10	13	12	3	8	10	1	57	8,143	8
Testing facilities and testing rules	8	3	9	5	9	14	9	57	8,143	9
Handling of chemicals in chemical lasers	16	1	15	1	1	11	15	60	8,571	10
Robustness	9	10	10	4	16	13	8	70	10,000	11
Collateral damage	11	15	8	9	10	16	3	72	10,286	12
Wall plug efficiency	14	16	16	2	3	5	16	72	10,286	13
Size	13	12	11	7	15	4	12	74	10,571	14
Necessity for lengthy vulnerability studies	15	2	13	8	12	15	13	78	11,143	15
Cost	12	14	14	6	14	9	14	83	11,857	16

Table 25: Round 3 Q1 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.167$

$X^2 = 17.596$

p-value= 0.284.

A sensitivity analysis was performed, and it was learned that by excluding respondent GO1's answers W will be 0.35 which is still regarded as poor agreement. However, by disregarding GO1's answers, the p-value was 0.0079 which is below the validity threshold of 0.05. Exclusion of other respondents did not have a significant effect on the W or p, and neither did the exclusion of any single factor.

Answers to Q2

The answers for Q2: *'Year when laser weapons will be commonly used by the military?'* are depicted in the diagram below.

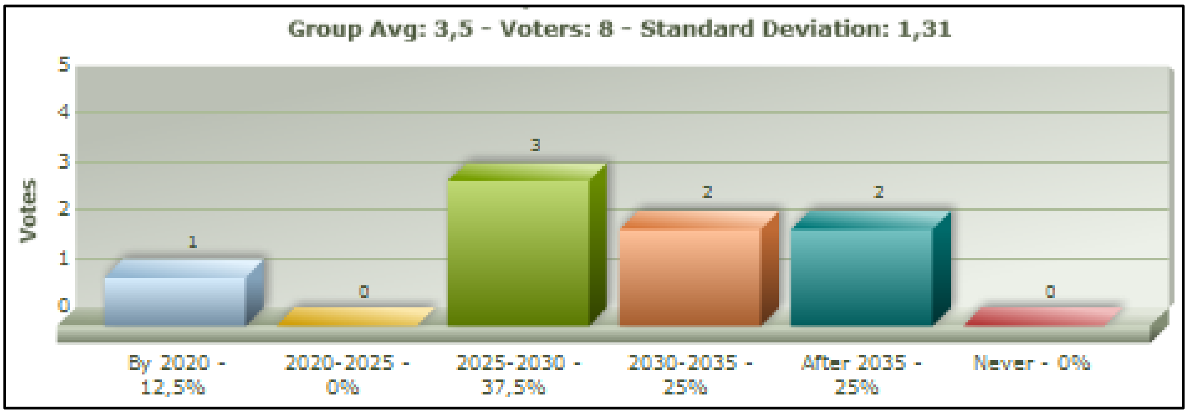


Figure 29: Round 3 Q2 Answers.

Answers to Q3

The answers for Q4: *'Year when land based laser weapons are mature enough to be used for air defence?'* are depicted in the diagram below.

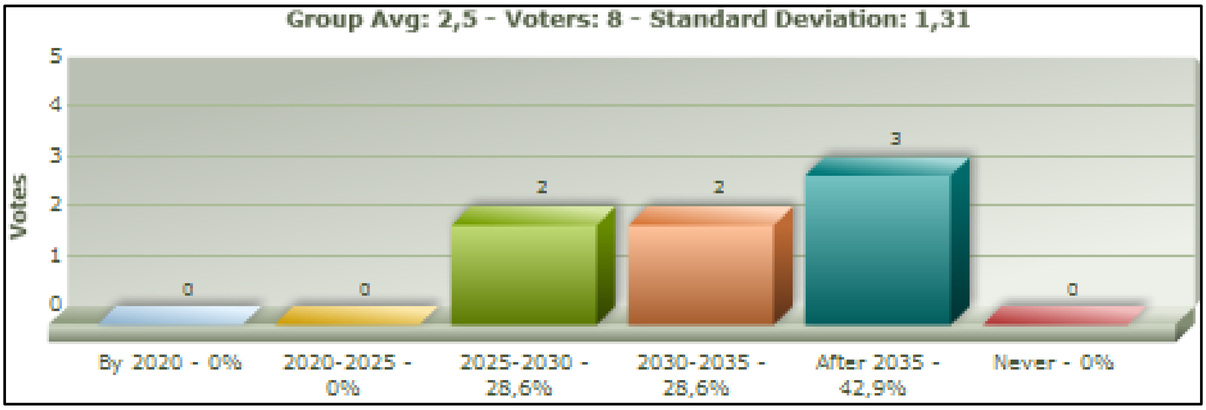


Figure 30: Round 3 Q3 Answers.

Answers to Q4

In Q4 of Round 3, the panellists were given four factors to be ranked. The answers for Q4: *'Rank the following factors advancing HPRF weapon maturity in order of significance'* are depicted in the table below.

Factor	Respondents							Sum of ranks	Mean rank
	39U	6XA	9GC	CWU	F9C	GO1	HP2		
Duality : Radar / Telecom.	3	3	3	4	4	1	1	19	2,714
Development of Solid state device (amplifier)	1	1	1	3	1	3	3	13	1,857
Relative simplicity compared to laser	4	2	2	1	3	2	2	16	2,286
Relatively cheaper than laser	2	4	4	2	2	4	4	22	3,143

Table 26: Round 3 Q4 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.18$

$X^2 = 3.85$

p-value= 0.27

Answers to Q5

In Q5 of Round 3, the panellists were given the same 11 factors as in Round 2 to be ranked. The answers for Q6: *'Rank the following factors hindering HPRF weapon maturity in order of significance'* are depicted in the table below.

Factor	Respondents							Sum of ranks	Mean rank
	39U	6XA	9GC	CWU	F9C	GO1	HP2		
Antenna	6	8	8	8	7	11	6	54	7,714
Buyers' hesitation to order/invest	7	3	1	1	9	7	1	29	4,143
Computing capability	2	2	6	3	1	3	7	24	3,429
Demanding power consumption	9	9	7	9	5	8	9	56	8,000
EM Compatibility with the platform	1	5	4	5	11	1	2	29	4,143
Frequency/wavelength	3	6	3	2	2	2	3	21	3,000
Lack of directionality	4	4	2	4	8	6	5	33	4,714
Modulation	8	7	5	6	3	4	4	37	5,286
Power	11	11	10	11	6	10	11	70	10,000
Reliability	5	1	9	7	10	5	8	45	6,429
Size	10	10	11	10	4	9	10	64	9,143

Table 27: Round 3 Q5 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.52$

$X^2 = 36.7$

p-value= <0.001

A sensitivity analysis was performed, and it was learned that by excluding respondent F9C's answers W would be 0.72 which is regarded as strong agreement. Exclusion of other respondents did not have a significant effect on the W- value.

Answers to Q6

The answers for Q7: *'Year when HPRF weapons are commonly used by the military?'* are depicted in the diagram below.

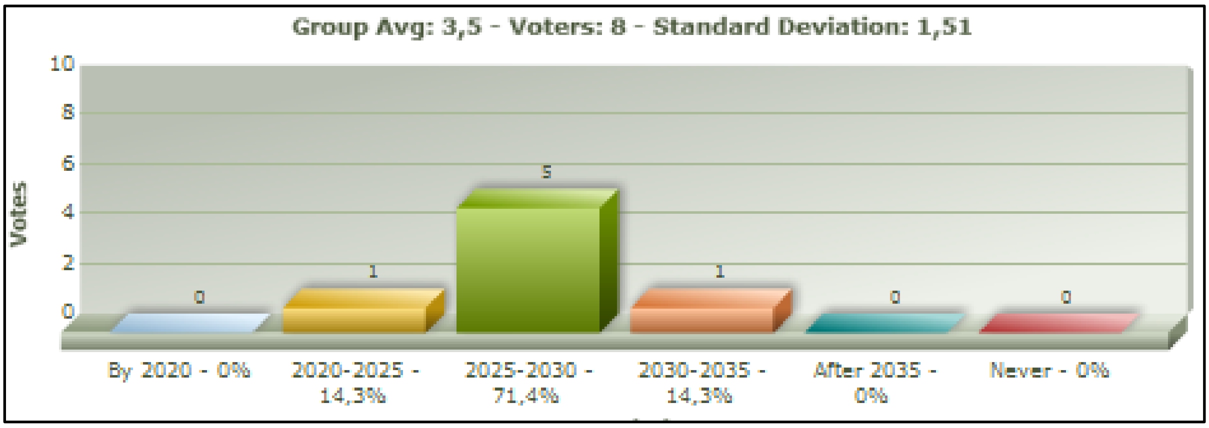


Figure 31: Round 3 Q6 Answers.

Answers to Q7

The answers for Q7: *'Year when land based HPRF weapons are mature enough to be used for air defence?'* are depicted in the diagram below.

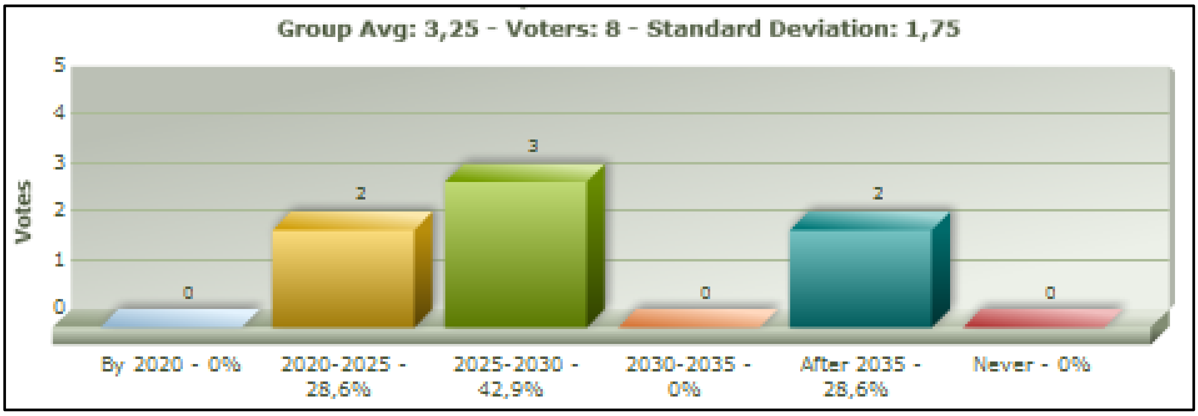


Figure 32: Round 3 Q7 Answers.

<u>Answers to Q8</u>

In Q8 of Round 3, the panellists were given 15 factors to be ranked. The answers for Q9: *'Rank the following non-technical factors that influence/could have an impact on the proliferation of DEW in order of significance'* are depicted in the table below.

Factor	Respondents							Sum of ranks	Mean rank
	39U	6XA	9GC	CWU	F9C	GO1	HP2		
Acceptability by the Military community: even if the technology would be mature, the way to do defence is related to tradition	1	13	15	14	14	15	10	82	11,714
Access to high power single mode lasers could limit proliferation due to the high cost of development	11	9	10	15	10	8	15	78	11,143
Airspace control	8	11	8	6	12	14	9	68	9,714
Civilian technology's (gps, wifi, mobile networks, ...) vulnerability to HPRF weapons	6	8	9	7	9	7	11	57	8,143
Fratricide and collateral damage behind target	13	1	3	11	4	6	5	43	6,143
Health and safety concerns for operators	4	3	7	10	3	5	6	38	5,429
High cost	12	6	5	13	7	11	12	66	9,429
Legislation	5	5	6	4	6	10	2	38	5,429
Operational concepts underpinning a safe and secure way of using it	9	7	11	9	8	12	13	69	9,857
Possible extension of the Geneva protocol on blinding lasers	3	4	4	2	5	3	7	28	4,000
Robustness. Higly technival devices have some mean time between failure. The length of MTBF will strongly affect the user experience	10	10	12	12	11	13	14	82	11,714
Rules of Engagement	7	2	2	8	2	2	3	26	3,714
The moral aspect as a hinder: An impression amongst the public that DEW are immoral/dirty weapons that may target or injure innocent people, or that they may cause unnecessary pain.	2	12	14	3	13	4	1	49	7,000
Use of chemicals and control of it	14	15	13	1	15	1	8	67	9,571
Weather. Clouds, rain etc.	15	14	1	5	1	9	4	49	7,000

Table 28: Round 2 Q8 Answers.

The following values were computed to assist in statistical analysis:

$W = 0.36$

$X^2 = 35.5$

p-value= 0.0012.

4.4.1. Summary of Round Three

Round three consisted eight questions including both attribute rankings and year estimations. The year estimations were iterated for the third time as they were incorporated in both previous rounds too. On the other hand, this was the second iteration of the attribute rankings as they were not included in Round 1. Round three provided sound data for an overall analysis which will be performed in the results chapter. By performing the third Delphi round, we met the fourth stopping criterion, ‘When we reach Round three’ as established in chapter 4.1. Based on meeting the stopping criterion Round three is the final Delphi round of this research

4.5. Technology Readiness Level (TRL) Assessment of Current DEW Systems

In this chapter, the Technology Readiness Levels of DEW systems are assessed. The assessment of individual system is performed by inserting publicly available data into USAF TRL calculator. We begin by introducing the calculators operating principles.

The calculator is based on MS Excel, and it consists of a summary sheet and data sheet. In the summary sheet, the user can choose which elements are included in the assessment. For this research, only technological readiness was chosen, and both manufacturing and programmatic levels were omitted. The set points for green/yellow were set to 85%/green and 67% for yellow. These colours indicate when the set percentage of a given TRL level is reached. The baseline values for this research are illustrated, as seen in the calculator, in Figure 33.

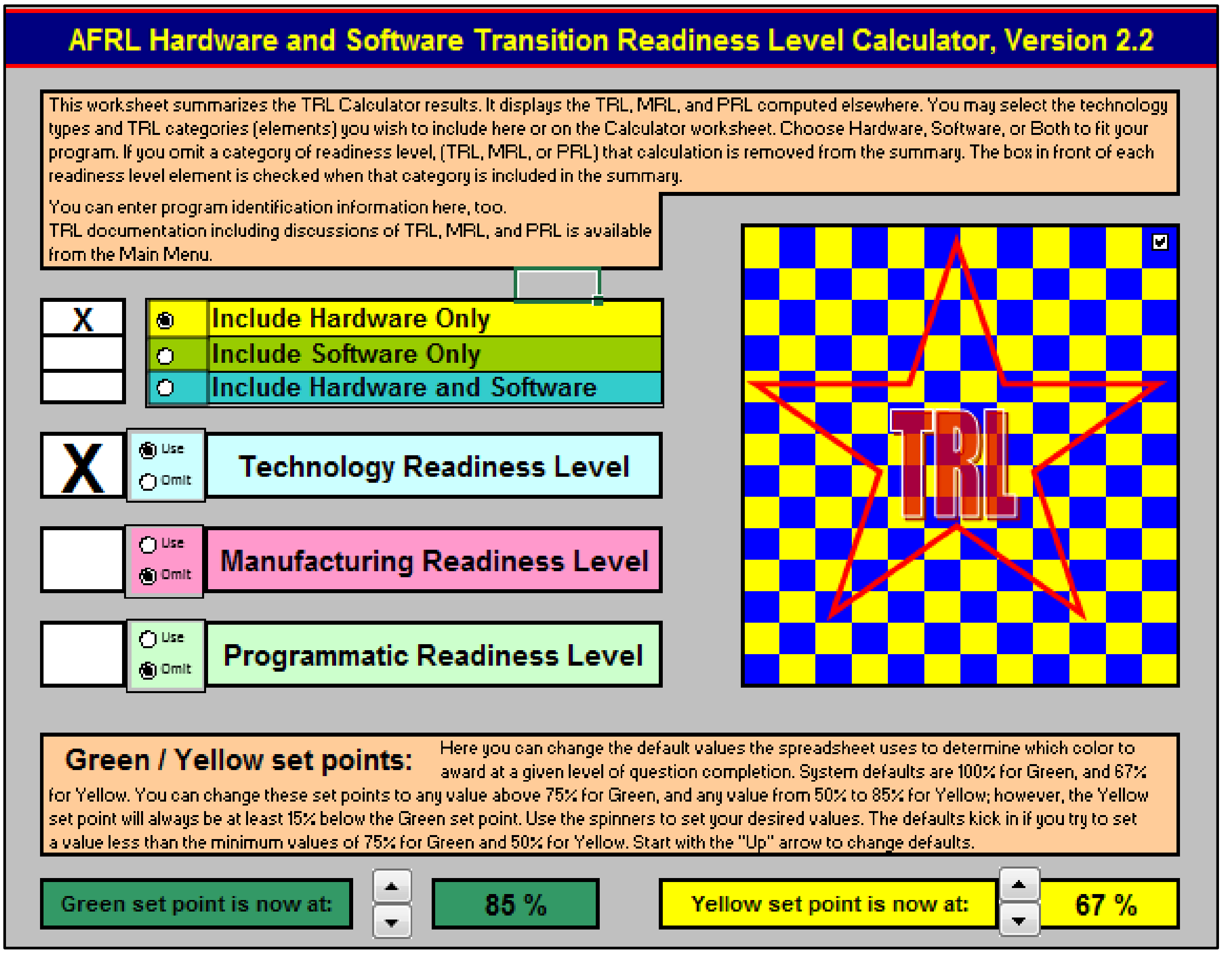


Figure 33: Baseline values for USAF TRL Calculator.

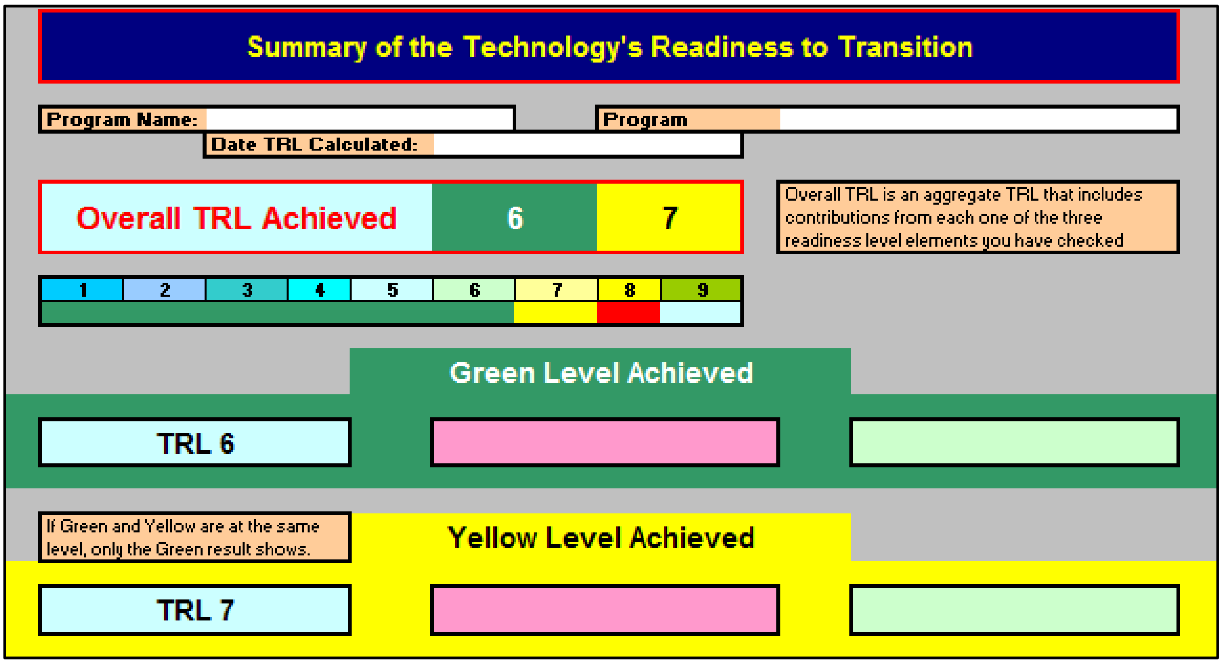


Figure 34: Summary View of USAF TRL Calculator.

Figure 34 depicts an example of the summary view. In this specific case, the calculator indicates green for TRL6 and yellow for TRL7. This means the system has fulfilled at least 85% of requirements for TRL6 and at least 67% of the requirements for TRL7. Consequently, we can state that the system is solid TRL6 and nearing TRL7.

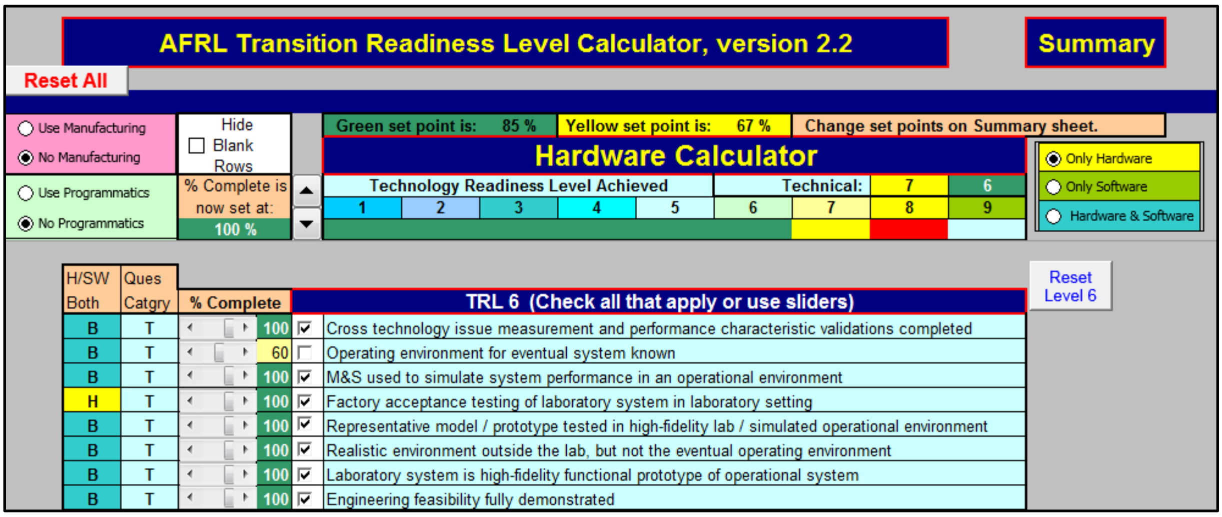


Figure 35: Example of Data View of USAF TRL Calculator.

In Figure 35 we can see an example of TRL6 questions and how they are shown in the data sheet. A given requirement is checked when it has been met. If a requirement is partially fulfilled, it is possible to indicate this in percentages. This allows a more detailed monitoring of the programme maturity development. In this research, as we relied solely on publicly available information, requirements were deemed either completed or not, and no percentages were used.

Table 29 includes the assessed TRL together with the justification for the given TRL. The systems/programmes are based on the findings of the literature review including most of the programmes introduced in Table 4 and Table 5. However, few of the programmes of literature review were excluded as adequate information was not available to assess their technological maturity.

Programme Name	TRL	TRL Justification	Remarks
HPM Demonstrator [29]0	7	TRL 7 fully met. Some TRL 8 steps also taken.	
ABL (Airborne Laser)	6/7	TRL 7 met apart from “components are representatives of production components”. Some TRL 8 steps also taken.	Program cancelled
ATL (Advanced Tactical Laser)	6/7	TRL 7 met apart from “components are representatives of production components”. Some TRL 8 steps also taken.	Program cancelled
CHAMP (Counter-electronics High-powered Advanced Missile Project)[20][60]	6/7	Solid TRL 6. Most of TRL 7 requirements met.	
HELE/LWM (High Energy Laser Effector/Laser Weapon Module) [54]	6/7	Solid TRL 6. Most of TRL 7 requirements met.	
LAWS (LAser Weapon System) [47]	6/7	TRL 6 fully met. TRL 7 met apart from “components are representatives of production components”.	
GBAD DE OTM (Ground Based Air Defence Directed Energy On The Move) [48]	6	Solid TRL 6. Many of TRL 7 requirements met.	
HELLADS (High Energy Liquid Laser Air Defense System) [61] [31]	5/6	TRL 5 fully met. TRL 6 mostly met and also some requirements of TRL 7.	
MLD (Maritime Laser Demonstrator) [47]	5	TRL 5 fully met. Only a few of TRL 6 requirements are met.	
RELI (Robust Electric Laser Initiative) [69][69]	4/5	Solid TRL 4. Most of TRL 5 requirements met.	
DPAL (Diode Pumped Alkali Laser)	4/5	Solid TRL 4. Most of TRL 5 requirements met.	
Gamma [46]	3/4	TRL 3 fully met. Most of TRL 4 requirements met.	
LDEW (Laser Directed Energy Weapon) [72]	3	Solid TRL 3.	
FEL (Free Electron Laser)[2][33]0	2/3	TRL 2 fully met. Most of TRL 3 requirements met.	

Table 29: TRL Assessment of DEW Programmes.

4.5.1. Summary of TRL Assessment

A USAF TRL calculator was used to discover the current TRL’s of DEW systems. The values inserted to the calculator were based on public information, and thus not all the information was available. It was established that the readiness levels range from TRL2 up to TRL7. Out of the 14 systems assessed 50% were between TRL6 and TRL7. The results together with their implications are covered in the results chapter.

5. RESULTS AND DISCUSSION

"We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run."

Roy Namara (1925-2007)

In this chapter, the results of the literature review together with the results of the Delphi survey and TRL assessment are introduced in respective sub-chapters. This is followed by a discussion where the results are combined, and their meaning is analysed. In addition, individual answers to research questions are provided.

5.1. Findings of the Literature Review

The literature review was conducted to find answers to sub-question 1 'What are the technologies and systems under development for AA and CRAM?' and to aid in composing the questions for the Delphi survey. As a consequence, there was a need to investigate the basic operating and scientific principles of directed energy weapons and to obtain information on the current status of relevant DEW programmes accompanied with insight on the DEW technologies' advantages and shortfalls. It was concluded that:

- For this study, the definition for DEW is adopted from US DoD Joint Publication 1-02 as: 'A weapon or system that uses directed energy to incapacitate, damage, or destroy enemy equipment facilities, and/or personnel.'
- DEWs cannot be categorised solely under non-kinetic weapons as there are also kinetic DEWs
- The most prominent and mature DEW technologies today are High Energy Lasers (HEL) and High Power Radio Frequency Weapons (HPRF)
- Numerous ongoing programmes are developing HEL systems accompanied with a smaller number of HPRF programmes
- Both HEL and HPRF have a solid scientific foundation, and their utility as weapons have been researched for decades
- There are some functioning DEW demonstrators
- Despite the lengthy research and testing many obstacles remain to mature the technologies to the level where they could be deployed
- Output powers of current DEW are far from being adequate in engaging manned aircraft size targets
- In general high energy lasers (HEL) are categorised into four classes. These are Solid State Laser (SSL), Dye/Liquid Laser, Gas Laser and Free Electron Laser (FEL)

- There are four categories of HPRF weapon effects: upset, lockup, latch-up and burnout
- Advantages of DEW include: Collateral damage reduction, Infinite magazine, low engagement price, beam travels at a speed of light, ability to engage multiple targets simultaneously and silence
- Disadvantages of DEW include: Size, weight and power (SWaP) issues, cooling related to excess heat, precision tracking requirements due to narrow beam, collateral damage and fratricide issues, need for a line of sight, limitations in range and weather related power losses
- Although there are some surveys made no unclassified DEW maturity studies have been published thus far

It was discovered that the DEWs are of interest especially to the US military and all US Services have their ongoing DEW programmes. This results in a rather complex array of both separate and interlinked programmes. US Air Force was the first Service pursuing to develop a DE system, and their chemical laser systems reached rather high technology readiness levels already in the early 1990's. These were followed by airborne applications in the 2000's. However, these programmes were then cancelled due to issues/restrictions related to chemical laser technology. Currently, naval applications are the most prominent and mature, especially when lasers are in question. This is mostly due to certain SWaP- related advantages in integration to ships compared to land or air platforms.

5.2. Results of the Delphi Method

In this chapter, the results of the Delphi method are introduced and discussed. The Delphi consisted both classic forecasting and ranking type questions, and their results are covered in separate sub chapters.

5.2.1. Results of Classic Forecast Delphi Questions

In total there were four classic Delphi questions which were used to provide an estimated timeframe when a certain technology would be in use. There were two questions for laser and two for HPRF weapons. The first question sought an estimated timeframe for the use of the particular technology in general while the second question regarded the use of the same technology in countering manned size aircraft. As stated in chapter 2.2, the median is considered to represent the group response in classic type Delphi, and thus it is implemented in the following.

The results of each round to question "*Year when laser weapons will be commonly used by the military?*" are depicted in Figure 36. The results indicate the development of answers towards later years as the iteration progresses. Furthermore, the results also converge as the theory behind Delphi suggests. The median in round one is the year 2025 while it shifted to 2030 in the final round. The results of the final round do not portray full consensus as the panellist answers range across the scale. However, as discussed in chapter 2.2, unanimous Delphi results rarely surface. It follows that the results allow us to conclude, based on the median that the panellists consider the laser weapons to be commonly used by the military in the year 2030.

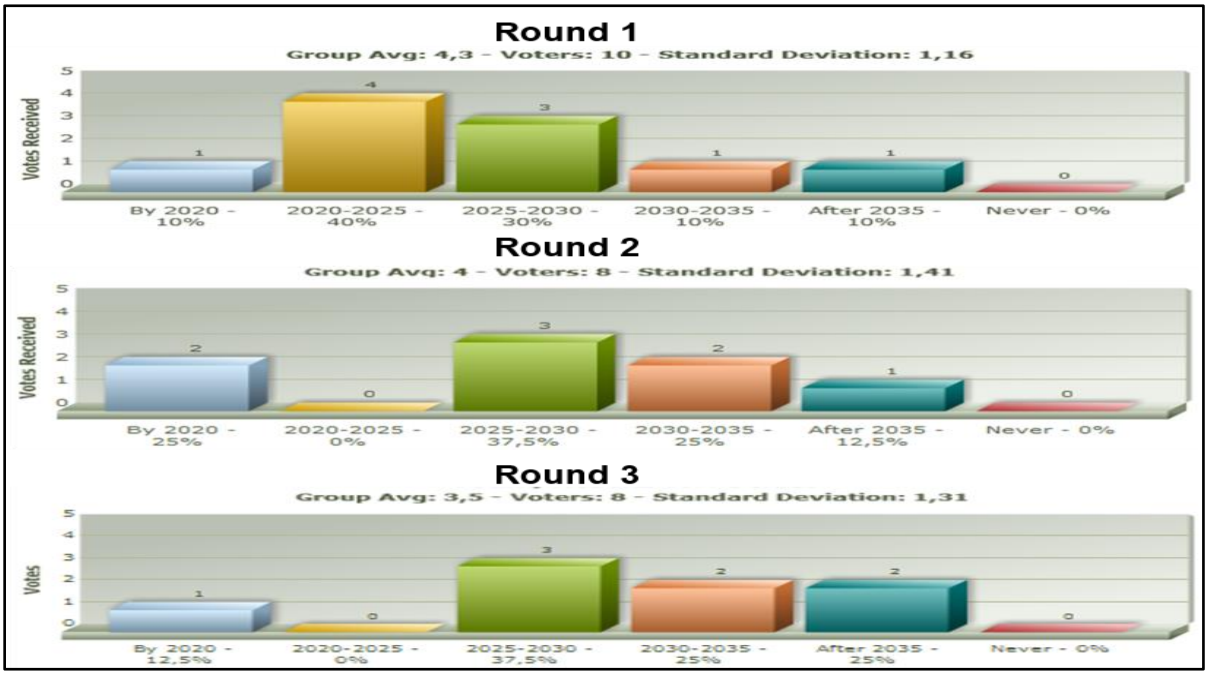


Figure 36: The Development of Answers to: "*Year when laser weapons will be commonly used by the military?*"

The results of each round to question "*Year when land based laser weapons are mature enough to be used for air defence?*" are depicted in Figure 37. The development of the answers to this question is again following the principles of the Delphi method. A clear change to a more shared view can be seen as all answering options are used in round one while only three options are used in the third round. It is also noteworthy that the median answer shifts towards a later date as the iteration advances. Based on the answers given by the panellists we can conclude that they estimate land based laser weapons to be mature enough for air defence in the year 2030-2035.

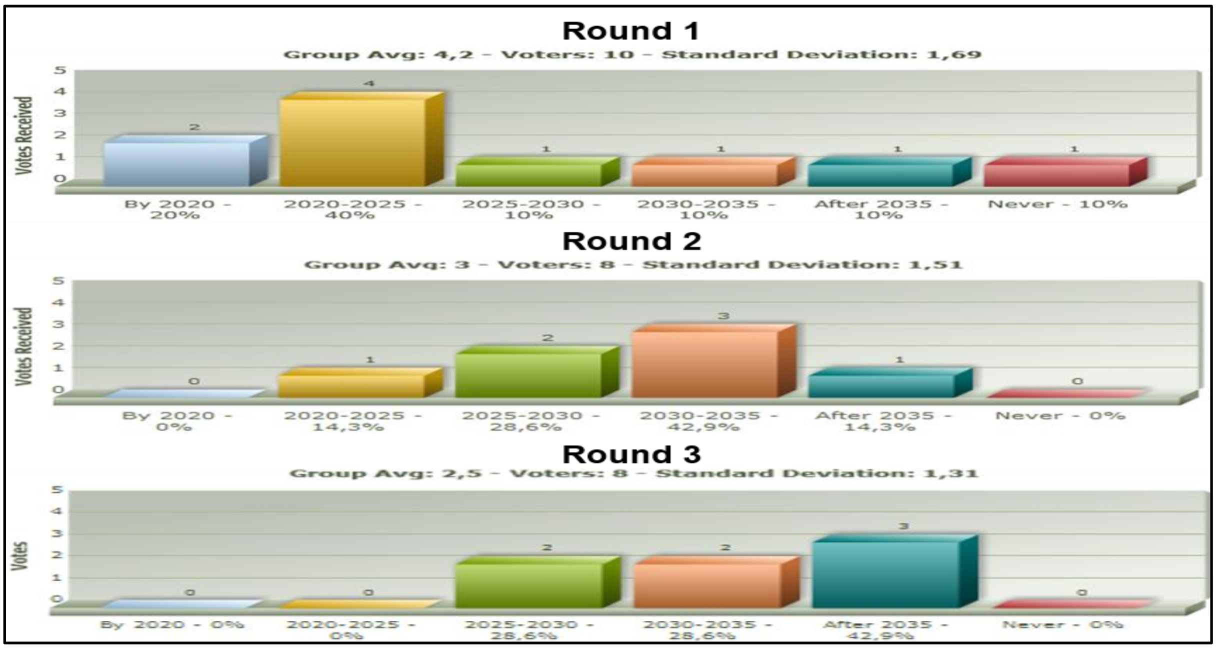


Figure 37: The Development of Answers to: "*Year when land based laser weapons are mature enough to be used for air defence?"*

The other two classic Delphi questions were HPRF- related. The results of each round to question "*Year when HPRF weapons are commonly used by the military?"* are depicted in Figure 38. Again the development of the answers portrays the principles of the Delphi method as the answers clearly converge from the outset. In fact, the third round shows significant consensus amongst the panellists as over 70% have chosen the same answer. Also in this question, the median answer shifts towards a later date as the iteration advances. As a conclusion, the panellists state HPRF weapons will be commonly used by the military in the year 2025-2030.

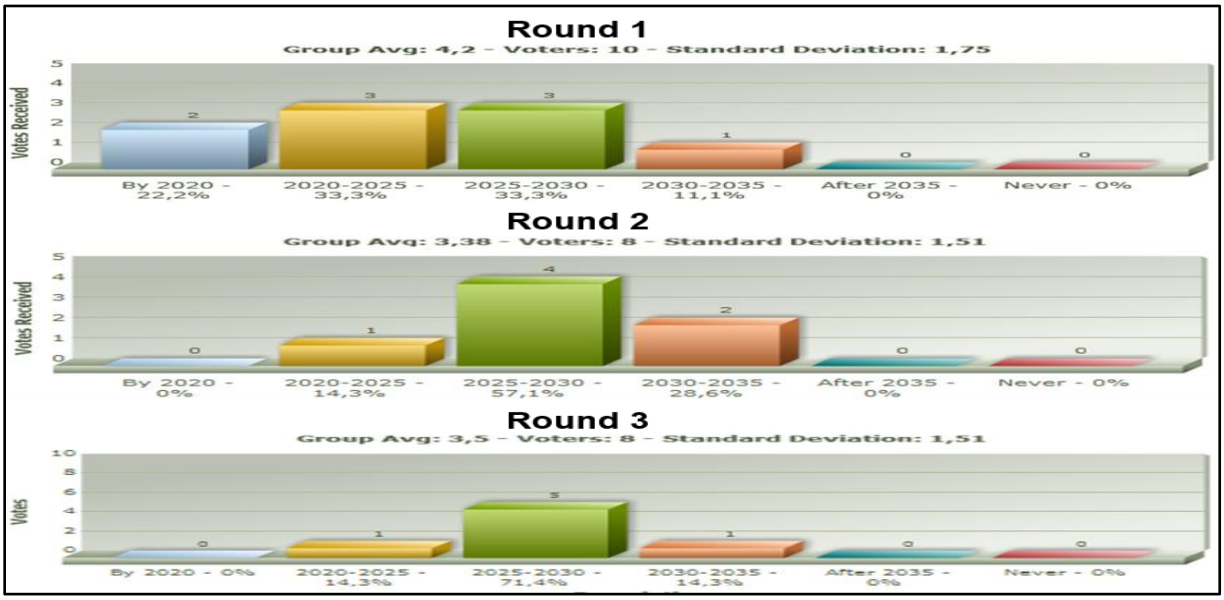


Figure 38: The Development of Answers to: "*Year when HPRF weapons are commonly used by the military?"*

The results of each round to question "*Year when land based HPRF weapons are mature enough to be used for air defence?"* are depicted in Figure 39. Again we can see the development of the answers indicating convergence from the outset. However, unlike the other three results, in this question, the final round indicates two alternate versions of the forecasted future. This is a phenomenon sometimes accompanied with forecast Delphi. It follows that we have two somewhat opposing views that need to be considered when the overall results are discussed. Nonetheless, again based on the median, the panellists view that HPRF weapons are mature enough to be used for air defence in the year 2025-2030.

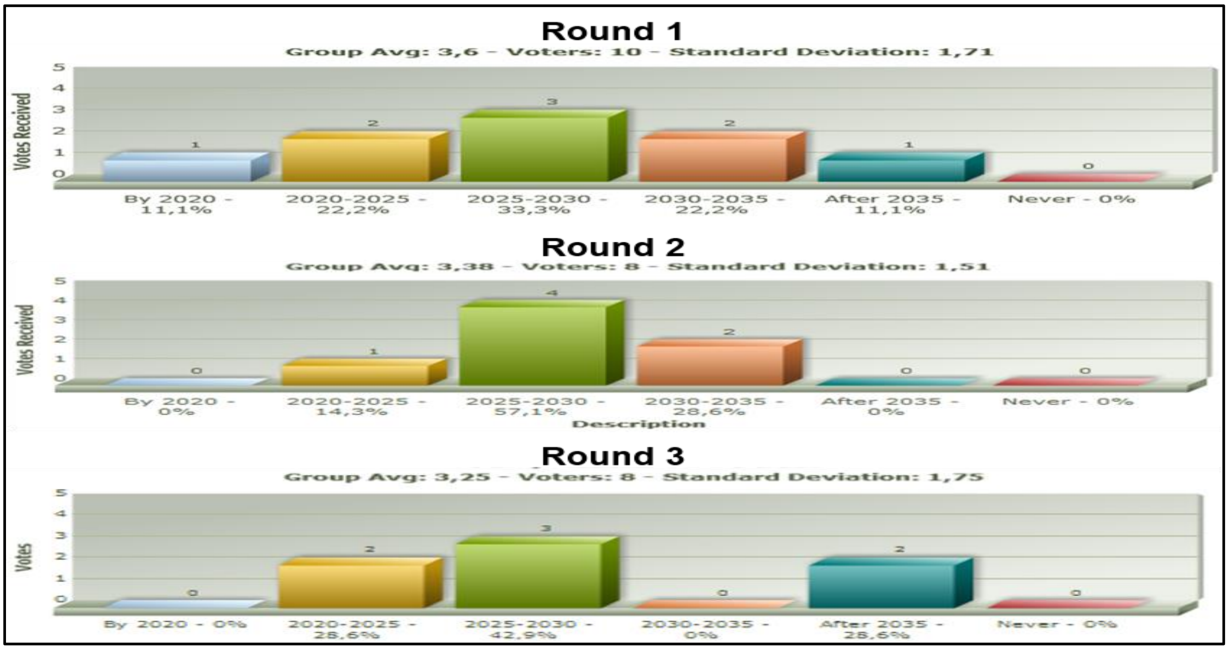


Figure 39: The Development of Answers to: "*Year when land based HPRF weapons are mature enough to be used for air defence?"*

5.2.2. Results of Ranking Delphi Questions

The Delphi rounds included a total of five ranking type questions. In Round 1 the panellists were given specific topics and asked to name topic related factors. These factors were clustered by the researcher and then sent to be ranked and iterated in the following rounds. An exception was made regarding one question. The question *'Rank the following factors advancing laser weapon maturity in order of significance'* was not send to iteration after second round as the results showed strong conformance after Round 1. The results of the ranking type questions are introduced and discussed next.

The first ranking question was *'Rank the following factors advancing laser weapon maturity in order of significance'* consisting of only two factors. Its final results are depicted in Table 30. The first round gave a *W*-value of 0.5625 (p= 0.034) but after sensitivity analysis, disregarding answers of 9GC, the *W*-value peaked to 1.00 (p=0.008) meaning full conformance. This meant that we had reached a stopping criterion and the particular question was not send for further iteration. Hence we conclude that the panellists were in strong agreement that increase in computing power is the main enabler to mature laser weapons.

Panellists	Computer power, increased computing power solves some of the challenges with laser	Industrial laser development
0JV	1	2
39U	1	2
6XA	1	2
9GC	2	1
CWU	1	2
F9C	1	2
GO1	1	2
HP2	1	2

Table 30: Final Answers to: *'Rank the following factors advancing laser weapon maturity in order of significance'.*

The next ranking question was: *'Rank the following factors hindering laser weapon maturity in order of significance'*. This question included 16 factors to be ranked in Round 2, and it was iterated in Round 3. The first ranking gave a W-value of 0.2412 (p=0.046), and after iteration, the W was 0.167, (p=0.28) both indicating poor agreement. Sensitivity analysis revealed that there was an only small change for the better if any single respondent was excluded. Therefore it was concluded that the panel did not reach consensus regarding the importance of the factors. However, the list is based on the factors provided by the panellists in Round 1, so the factors themselves are valid. The results are shown in Table 31.

Factor	Respondents							Sum of ranks	Mean rank	Rank	Tier
	9GC	39U	6XA	GO1	CWU	F9C	HP2				
Precision tracking for range performance	4	7	2	10	13	1	2	39	5,571	1	1
Beam quality (Raman scattering, blooming)	5	8	3	14	6	2	4	42	6,000	2	
Adapive optics and beam combining	3	5	6	16	7	3	6	46	6,571	3	2
Power consumption	2	9	5	13	2	7	10	48	6,857	4	
Cooling/Waste heat	7	4	7	11	4	12	5	50	7,143	5	
Buyers' hesitation to order/invest	6	11	1	12	5	8	7	50	7,143	6	
Sufficient output level	1	6	4	15	11	6	11	54	7,714	7	3
Mobility	10	13	12	3	8	10	1	57	8,143	8	
Testing facilities and testing rules	8	3	9	5	9	14	9	57	8,143	9	
Handling of chemicals in chemical lasers	16	1	15	1	1	11	15	60	8,571	10	
Robustness	9	10	10	4	16	13	8	70	10,000	11	4
Collateral damage	11	15	8	9	10	16	3	72	10,286	12	
Wall plug efficiency	14	16	16	2	3	5	16	72	10,286	13	
Size	13	12	11	7	15	4	12	74	10,571	14	
Necessity for lengthy vulnerability studies	15	2	13	8	12	15	13	78	11,143	15	5
Cost	12	14	14	6	14	9	14	83	11,857	16	6

Table 31: Final Answers to: *'Rank the following factors hindering laser weapon maturity in order of significance'.*

Since the required level of agreement was not reached, there was a need to examine the factors' relative importance by other means. Hence tiers based on significant gaps between the mean ranks were generated. It was decided that 0.5 would be considered as a significant gap between consecutive mean ranks. These gaps are marked in the matrix with a red line. The line also separates the tiers. Each tier encompasses factors that are considered equally important. Because of the decided gap of 0.5 some tiers include only single a factor. The tiers are in order of significance from the top down. For example, we can state that the panel considers 'cooling/waste heat' (Tier 2) to be a more significant factor than 'mobility' (Tier 3). However, due to poor *W*- value, we cannot determine the order of the factors within a particular tier.

In total six tiers were identified, and they formed the basis for further analysis. Firstly, it is evident that the panel considers the cost to be the least hindering factor for laser weapon maturity. This is also quite natural as the price of the system is relative to what kind of capability it can provide together with the life cycle costs related to it. Thus when laser weapons are up to their promises, a price most likely will not be a factor.

A second notion regards the factor concerning the handling of chemical lasers. The replies are quite evenly divided into both end of the spectrum, the factor was either considered very important or totally irrelevant. This is likely due to the reason that all respondents are aware of the problems related to toxic chemicals, but some consider it no longer a factor as their use has virtually ended. Nonetheless, as toxic chemicals are not used in systems under development, this factor does not require further consideration.

A peculiar notion is that although power consumption and wall-plug efficiency are basically the same thing they are quite far on the table. Their marriage results from the fact that if a system has a good wall-plug efficiency, it consumes less power. Most likely respondents unfamiliar with the term 'wall-plug efficiency' ranked it to be the least significant. In retrospect, these factors probably should have been aggregated before Round 2. Nonetheless, power consumption was seen significant and it is in the 2nd tier, so the location of wall-plug efficiency in tier 4 is not changing the big picture.

As a whole, the greatest issues were seen to relate to optics, beam quality and precision tracking. These all are affecting laser weapons ability to function as an effector. Therefore it can be said that the panel also identified the most vital factors for the laser to serve as a weapon.

Third ranking question inquired panellists' perception about issues relating to advancing HPRF weapons' maturity and was: *'Rank the following factors advancing HPRF weapon maturity in order of significance'*. This question consisted of 4 factors that were ranked in Round 2 and then further iterated in Round 3. The first ranking gave a W-value of 0.086 (p=0.61), and after iteration, the W was 0.183 (p=0.28) both indicating very poor agreement. Sensitivity analysis revealed that there was an only small change for the better if any single respondent was excluded. Therefore it is evident that the panel did not reach consensus regarding the importance of the factors. However, the list is based on the factors provided by the panellists in Round 1, so the factors themselves are valid. The results are shown in Table 32.

Factor	Respondents							Sum of ranks	Mean rank	Rank
	39U	6XA	9GC	CWU	F9C	GO1	HP2			
Development of Solid state device (amplifier)	1	1	1	3	1	3	3	13	1,857	1
Relative simplicity compared to laser	4	2	2	1	3	2	2	16	2,286	2
Duality : Radar / Telecom.	3	3	3	4	4	1	1	19	2,714	3
Relatively cheaper than laser	2	4	4	2	2	4	4	22	3,143	4

Table 32: Final Answers to: *'Rank the following factors advancing HPRF weapon maturity in order of significance'.*

Due to the poor W –value the results could be analysed utilising the same approach as before, by identifying significant gaps in the mean ranks. However, in this case, the approach was unfertile as there were no gaps which exceed the agreed 0.5 level. It follows that we can only state that the panellists concur their earlier view regarding the price factor. A high price was not regarded as a remarkable factor in hindering the advancement laser, and on the other hand, the possible low price of the HPRF weapons is not seen advancing HPRF maturity. In other words, it stresses the earlier notion of price-capability ratio.

The next ranking question covered the hindering factors to HPRF weapon maturity. It contained 11 factors and asked: *'Rank the following factors hindering HPRF weapon maturity in order of significance'*. After Round 2 the W –value was 0.14 (p = 0.46) but it was significantly enhanced in Round 3 as it rose to 0.52 (p < .001) indicating modest agreement. By performing sensitivity analysis, it was learned that the exclusion of respondent F9C would indicate strong agreement with W=0.72 (p < .001). However, the sensitivity analysis also revealed that the exclusion of F9C would only change the order of the first four factors while the rest would remain the same. Thus it was decided to include all respondents but incorporate two different rank columns into the result table. The results are shown in Table 33.

Factor	Respondents							Sum of ranks	Mean rank	Moderate agreement Rank	Strong Agreement Rank
	39U	6XA	9GC	CWU	F9C	GO1	HP2				
Frequency/wavelength	3	6	3	2	2	2	3	21	3,000	1	1
Computing capability	2	2	6	3	1	3	7	24	3,429	2	
Buyers' hesitation to order/invest	7	3	1	1	9	7	1	29	4,143	3	
EM Compatibility with the platform	1	5	4	5	11	1	2	29	4,143	4	
Lack of directionality	4	4	2	4	8	6	5	33	4,714	5	2
Modulation	8	7	5	6	3	4	4	37	5,286	6	3
Reliability	5	1	9	7	10	5	8	45	6,429	7	4
Antenna	6	8	8	8	7	11	6	54	7,714	8	5
Demanding power consumption	9	9	7	9	5	8	9	56	8,000	9	6
Size	10	10	11	10	4	9	10	64	9,143	10	7
Power	11	11	10	11	6	10	11	70	10,000	11	8

Table 33: Final Answers to: *'Rank the following factors hindering HPRF weapon maturity in order of significance'.*

The 'Moderate agreement rank' refers to final ranking after Round 3 (W=0.52, $p < .001$)) showing individual ranking for all 11 factors. The 'Strong agreement rank' has the first four factors clustered under one rank meaning they are equally important. By aggregating the four first factors, we get W=0.72 ($p < .001$) indicating strong agreement. This allows the reader to compare the two alternatives and utilise the one that suits him/her the best. As per this research, the 'strong agreement rank' column is perceived to be more useful, and the following discussion is based on it.

Results wise the panel is in strong agreement of the presented factors and their ranking. By scrutinising the table, we can observe some factors of particular interest. The most noticeable results include 'power' and 'size' locating at the very bottom and with a clear margin. A conclusion can be drawn that power and size will not be major issues in HPFR maturing.

As for the group of four factors ranked as the most important, there do not seem to be a common nominator. The group includes wavelength, computing capability, EM compatibility as well as possible buyer hesitation. However, it is noteworthy that buyer hesitation is regarded a major factor, another common feature with laser weapons.

The final ranking was about non-technical factors covering DEWs in general. The question, *'Rank the following non-technical factors that influence/could have an impact on the proliferation of DEW in order of significance'*, included 15 factors. After Round 2 the W–value was 0.2 (p = 0.26) and it got up to 0.32 (p = 0.0012) after Round 3. Although the panel's opinion showed convergence, it did not reach even moderate level. Therefore there was a need to aggregate some factors into groups, and again the 0.5 was the value used for a significant gap. This resulted in seven tiers as illustrated in Table 34.

Factor	Respondents							Sum of ranks	Mean rank	Rank	Tier
	39U	6XA	9GC	CWU	F9C	GO1	HP2				
Rules of Engagement	7	2	2	8	2	2	3	26	3,714	1	1
Possible extension of the Geneva protocol on blinding lasers	3	4	4	2	5	3	7	28	4,000	2	
Health and safety concerns for operators	4	3	7	10	3	5	6	38	5,429	3	
Legislation	5	5	6	4	6	10	2	38	5,429	4	
Fratricide and collateral damage behind target	13	1	3	11	4	6	5	43	6,143	5	2
The moral aspect as a hinder: An impression amongst the public that DEW are immoral/dirty weapons that may target or injure innocent people, or that they may cause unnecessary pain.	2	12	14	3	13	4	1	49	7,000	6	3
Weather. Clouds, rain etc.	15	14	1	5	1	9	4	49	7,000	7	
Civilian technology's (gps, wifi, mobile networks, ...) vulnerability to HPRF weapons	6	8	9	7	9	7	11	57	8,143	8	4
High cost	12	6	5	13	7	11	12	66	9,429	9	5
Use of chemicals and control of it	14	15	13	1	15	1	8	67	9,571	10	
Airspace control	8	11	8	6	12	14	9	68	9,714	11	
Operational concepts underpinning a safe and secure way of using it	9	7	11	9	8	12	13	69	9,857	12	6
Access to high power single mode lasers could limit proliferation due to the high cost of development	11	9	10	15	10	8	15	78	11,143	13	7
Acceptability by the Military community: even if the technology would be mature, the way to do defence is related to tradition	1	13	15	14	14	15	10	82	11,714	14	
Robustness. Higly technical devices have some mean time between failure. The length of MTBF will strongly affect the user experience	10	10	12	12	11	13	14	82	11,714	15	

Table 34: Final Answers to: *'Rank the following non-technical factors that influence/could have an impact on the proliferation of DEW in order of significance'.*

The table shows clearly that the respondents' main worry is how DEW's and laser, in particular, will be perceived from the legislative perspective. Apparently, there are doubts or fears that the use of laser might be banned or restricted by international law. Three top tiers are more or less related to worries regarding legislation, policies, or public and user scepticism.

Another main non-technical issue with a rather high tier is concerning weather. Although it is only found in the 3rd tier, it is the first factor that is not human made. In another word, weather related issues are perceived as the main scientific factor that could prevent the widespread deployment of DEWs. On a further note, it is one of the rankings where the panel opinion is very controversial. Whereas two respondents view 'weather' to be very little of a factor by giving it ranks 14 and 15, other two ranks it as the most important factor. This is one of the reasons, but by no means the only one, behind the poor W –value for this ranking.

5.2.3. Summary of Delphi Results

The Delphi was used to establish scientifically valid information of the assessed maturity of DEW in the future together with estimated factors that could either advance or hinder the maturing. The main findings revealed by the Delphi were:

- Laser weapon will be commonly used by the military in 2030
- Laser weapons will be mature enough for air defence in 2030-2035
- HPRF weapons will be commonly used by the military in 2025-2030
- HPRF weapons will be mature enough to be used for air defence in 2025-2030
- Computing power is the main enabler for maturing laser weapons
- Price of the laser systems will not be a factor once the systems can provide the expected capability
- Power consumption of laser systems must be reduced to a reasonable level before widespread use
- Key issues preventing laser weapon maturity are related to optics, beam quality and precision tracking
- Price of the HPRF systems will not be a factor once the systems can provide the expected capability
- Regarding the DEW, in general, the main issues were related to legislation, policies and public/user scepticism
- The weather was the main scientific factor that could prevent the widespread use of DEWs.

The classic Delphi questions served their purpose well, and the respondent’s results were converging towards a common view. Based on the median of answers a panel opinion was formed which enabled us to answer SQ2. The ranking Delphi, however, was not able to yield consensus based rankings. Nonetheless, the analysis of the ranked lists allowed us to identify important factors for further discussion. As a whole, the Delphi rounds provided an excellent collection of results that can be contrasted with the results of other methods and discussed in chapter 5.4.

5.3. Results of TRL Assessment

Based on the table presented in chapter 4.5 we can conclude that the DEW programmes' TRLs range from 2 to 7. According to the material discussed in chapter 2.6, it takes between 6-9 years for a complex system to advance from TRL6 to TRL9 and between 6-16 years from TRL4 to TRL9 [43][44][9]. This does not, however, mean that maturing always occurs. On the contrary, many programmes are cancelled, due to various reasons, although having reached TRL6 or even above. This is also the case with some of the programmes presented in the table. It follows that we need to keep in mind that although TRL assessment can aid in drawing conclusions of the expected timeline, it does not tell anything about the likelihood of reaching the next TRL.

Figure 40 presents the assessed technology readiness levels together with the target size the systems are currently able to engage. The fourfold table indicates that there is only one system capable of reaching powers high enough (+500kW, the power requirements were discussed in chapter 3.2.3) to down a manned aircraft size target. That is the ABL, a programme that has been cancelled and most likely will not be continued. Furthermore, the only other system able to reach powers exceeding 100kW, the ATL, has also been cancelled. Both of these systems were gas lasers utilising highly toxic chemical fuel, and that laser technology has been declared more or less a dead end.

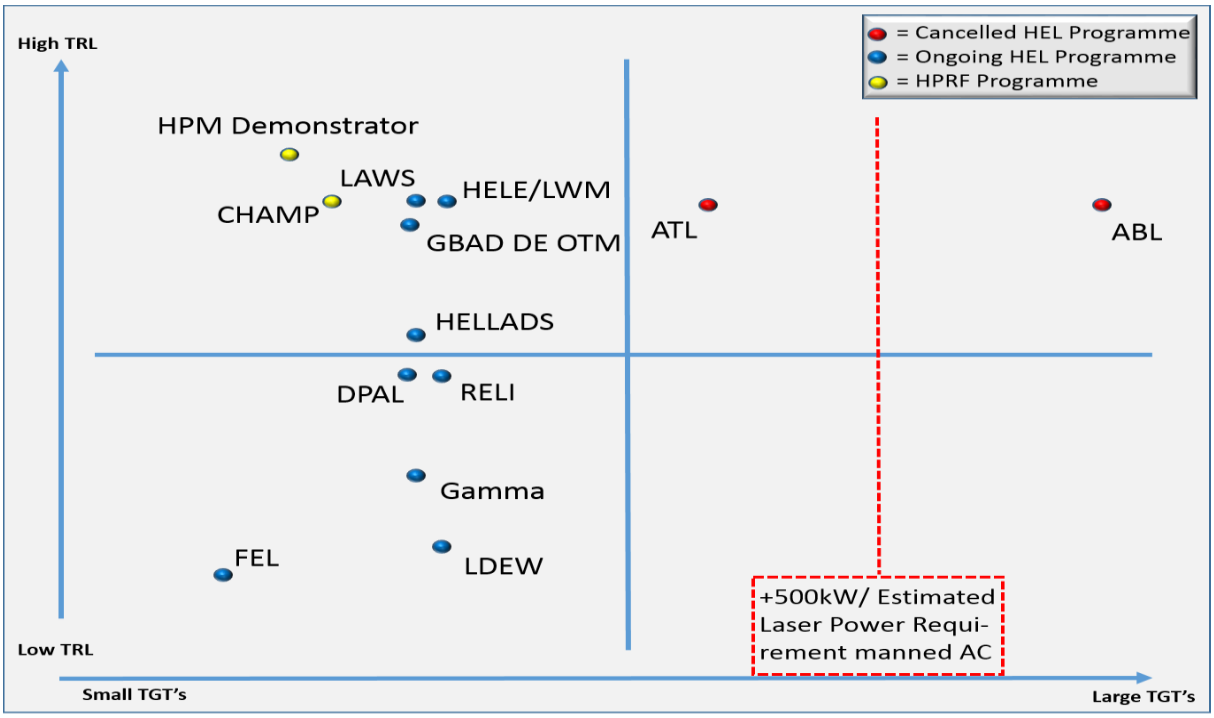


Figure 40: DEW Programmes' TRLs and Current Target Sizes.

On the other hand, there is a rather large number of systems/programmes under development. About half of these are above TRL 5 and some as high as TRL7. The time it will take in maturing these into TRL 9 depends on many variables, but probably the most significant are the aspired power level/size of the target. The programmes aiming for developing systems to counter small UAV have, in general, reached quite high TRL compared to programmes aspiring to attain the megawatt level. This phenomenon can be seen in Figure 41.

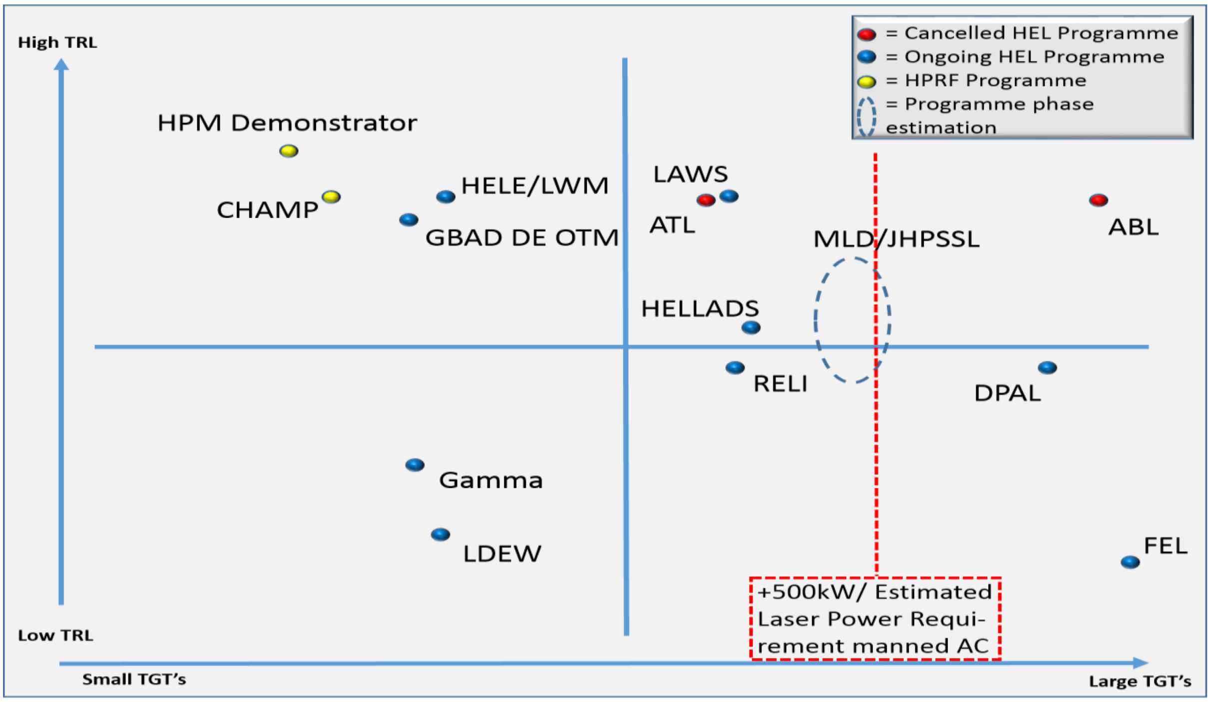


Figure 41: DEW Programmes' TRLs and Aspired Target Sizes.

In Figure 41, the programmes are placed on the same fourfold table as in Figure 40, but their location on the horizontal axis is based on the programme's power goal. The table also includes the estimated TRL of MLD/JHPSSL programme. Although there was not adequate information to assess its TRL by using the TRL calculator, the programme was included in the table because it has claimed to have the capability to reach the 500kW marker. The table enables us to divide the programmes into three main tiers based on their goals regarding power. The 1st tier contains systems aiming for powers more than 500kW, 2nd tier holds systems intending to reach 100-300kW and the 3rd tier consists of systems aiming for power less than 100kW.

We can establish that there are three ongoing programmes in the 1st tier and all possess a rather modest TRL. FEL is still to attain TRL 3, DPAL is between 4 and 5 while the MLD/JHPLSS is estimated in between TRL 4-6. The average TRL of tier one is 4.

There are three active programmes in tier two also, but their TRL's are higher compared to those of tier one. RELI's TRL is assessed to be the lowest but nonetheless, it is close to TRL 5 and LAWS is almost TRL 7. Tier two's average TRL is 5.5.

In the 3rd tier, we have six programmes with TRLs ranging from the LDEW's 3 to HPM demonstrator's 7. We can also identify that two programmes are significantly immature compared to the rest. If these two are not included tier three has an average TRL of 6.5, and if they are taken into account, then the mean TRL is 5.5. Tier three also encompasses two HPRF systems. It is noteworthy that their target size is not based on the power requirement chart presented in chapter 3.2.3 but on the literature review material of the respective systems. The material indicates that HPM Demonstrator is capable of downing small UAV [29] and since it is based on CHAMP their target sizes are somewhat the same.

A crucial variable which the tables does not illustrate is the range. Although some literature mentioned a range of a system, there still was not enough range information to be incorporated into a table. In general, however, a notion that the system's range is very much dependable on its output power was present. Thus cautious predictions can be made of the range of a particular system based on the power/target size. Based on Table 3 we can safely state that engagements over the distance of 5 km require several hundred kilowatts of power.

Moreover, as the assessment is based solely on publicly available information, there is a reasonable chance that not all the assessed TRL are true. As described in chapter 2.5 TRL assessment is a thorough process containing exhaustive amount of detailed information on the programme in question. Now only a small portion of this information was available, and there is also a possibility that the information is purposefully false or biased. Nonetheless, it was assumed that the used information received is adequately accurate and thus an assessment could be made to illustrate the general TRL's of current systems.

In conclusion, the TRL assessment suggests that maturing the current programmes from TRL6/7 into TRL9 will take approximately 6-12 years whereas for the systems with lower TRL it will be some14-20 years respectively. Furthermore, it is also concluded that the development of systems capable of countering small targets will reach TRL9 sooner than systems aspiring to down manned aircraft or cruise missiles.

5.4. Discussion of the Results

In this chapter, the results of all three utilised methods, literature review, Delphi and TRL assessment, are collated, contrasted and finally consolidated. The idea is to identify where the results of two or more methods support each other as well as where the results are contradictory. Furthermore, the findings are critically analysed, and the reasons behind them discussed.

Although it was decided to use multiple methods mainly to add validity this also provided resilience should any of the methods fail. None of them did fail, however, so we can use their results as originally planned.

We gained background information of the scientific foundation of DEW by performing the literature review, but it also provided us with sound results regarding the ongoing DEW programmes and their goals. It was learned that the scientific foundation of both HEL and HPRF weapons is solid and it is backed up with some 60 years of basic research. Also the literature review revealed there were at least 14 ongoing laser weapon programmes and five ongoing HPRF weapon programmes. The numbers speak for themselves; there is a true ambition to develop and field DEWs. To put another way, based on the number of programmes we can expect to see further showcasing of demonstrators and prototypes in the future. The DEW is becoming more and more prominent player especially as the UAV and swarming threats increase.

The classic part of the Delphi delivered what it was designed to do, year estimates about DEW maturity based on expert opinion. However, the ranking type Delphi was not able to fully live up to the expectations. It did provide the lists of significant factors regarding DEW maturity and proliferation, but the panel never reached consensus in ranking them. We can only speculate whether the answers would have displayed more convergence had we included more iteration rounds. However, this was not possible due to time restrictions. On the other hand, the respondents were so far from shared opinion that reaching consensus is unlikely even with further iteration.

Having said that, however, the ranking Delphi was by no means a total failure. After arranging the factors into groups or tiers, we were able to establish a ranking between the tiers. This enabled us to inspect the overarching topic of the tier and thus provided a possibility to pinpoint subjects of interest. The most significant ranking Delphi results included the following. Computing power is the most important factor in advancing laser maturity. Optics and beam quality are regarded as the main obstacles for laser. High price will not be a factor once the systems can deliver what expected and weather was considered as number one worry that is not humanmade. Moreover, finally, the panel stated their concern about numerous legislative and policy related issues. All of these findings provide the basis for discussion to either support or question the results of the other methods.

To provide an all-encompassing view of the main findings a table was composed. In the table, shown in Table 35, the main results of literature review, TRL assessment and Delphi are presented to provide a comprehensive but concise overview of the results.

Programme Name	Technology	TRL	Predicted capability in TRL9	Year for TRL9 based on TRL evolvement data	Year when in use based on Delphi
HPM Demonstrator [29]0	HPRF	7	Mobile C-UAS 2km	2021-2027	HPRF systems 2025-2030/ after 2035
CHAMP (Counter-electronics High-powered Advanced Missile Project)[20][60]	HPRF	6/7	Airborne latch-up 2km	2023-2029	
HELE/LWM (High Energy Laser Effector/Laser Weapon Module) [54]	HEL	6/7	N/A	2023-2029	Laser systems 2030-2035
LAWS (LAser Weapon System) [47]	SSL/Fibre HEL	6/7	Shipborne C-UAS 5km	2023-2029	
GBAD DE OTM (Ground Based Air Defence Directed Energy On The Move) [48]	Laser	6	Mobile C-UAS 3km	2023-2029	
HELLADS (High Energy Liquid Laser Air Defense System) [61] [31]	Liquid (Dye) Laser	5/6	Airborne C-RAM/C-UAS/ A/G 10km	2024-2030	
MLD (Maritime Laser Demonstrator) [47]	SSL laser	5	Shipborne Anti-aircraft and cruise missiles 8km	2024-2030	
RELI (Robust Electric Laser Initiative) [69][69]	SSL/Fibre laser	4/5	C-RAM/C-UAS 8km	2026-2032	
DPAL (Diode Pumped Alkali Laser)	Gas laser	4/5	Up to ballistic missile defence	2026-2032	
Gamma [46]	SSL laser	3/4	N/A	2029-2035	
LDEW (Laser Directed Energy Weapon) [72]	Laser	3	Shipborne C-UAS 5km	2029-2035	
FEL (Free Electron Laser)[2][33]0	FEL laser	2/3	Up to ballistic missile defence	2032-2037	

Table 35: Main Findings Combined.

The table consists of columns indicating all the programmes that are both ongoing and whose TRL were assessed in chapter 4.5. The literature review provided results for columns 1, 2and 4, TRL assessment contributed for columns 3, and the Delphi was the enabler for column 6.

The information in column 5 was formulated by combining results from the literature review and TRL assessment with the TRL evolvement data presented in chapter 2.6.

We can observe from the table that the results regarding years correlate quite well. The HPRF systems are regarded to enter TRL9 in 2021-2029 and perceived by the Delphi panel to be commonly in use in 2025-2030. However, in this particular case the Delphi results indicated two alternative outcomes, and while the median is 2025-2030, there was population stating that HPRF weapons would be in use only after 2035. Hence the table shows two results. Nonetheless, we can conclude that the timeline is logical and based on assuming TRL9 is reached in 2021-2029 it is plausible that HPRF weapons are commonly (10+ operational systems as defined in the questionnaire) in use in 2025-2030.

A similar phenomenon can be noticed regarding the laser systems. If the immature systems are excluded, the TRL9 year is assessed to be in 2023-2032 while the Delphi results state laser weapons are commonly in use in 2030-2035. Again the gap between assessed TRL9 and commonly in use is regarded credible. As a conclusion we can say that the results of TRL assessment and Delphi concur and complement each other.

In spite the results presented in the table we also have to take into account a variety of variables that may either accelerate or impede the maturing process. As for the pervasive use, we also have to consider factors like export restrictions and availability.

What comes to the maturing process, we can expect it to correlate to both existing and upcoming threats. This is because DEW’s are mainly, at least today, weapons designed to counter a threat be it UAV, RAM or some other air vehicle. Although some programmes are aspiring to develop an offensive DEW, at least CHAMP and HELLADS, the main driver for the emergence of DEW is defence. It follows that if there is a sudden introduction of DEW specific threats we are likely to witness rapid growth in funding and thus also earlier maturing. This is how militaries operate; once these threats either surface or they are forecasted to surface, militaries pursue to counter them, and DEW can provide a possible solution. Mainly these ‘new’ threats that can speed up the development are the increased use of UAVs and the introduction of salvo/swarming tactics related to UAV and missiles. Especially the escalation of UAV threat is expected to boost the development as there already are systems capable of downing small UAVs.

On the other hand, however, should we not witness the rise of the mentioned threats we may be looking at maturing rate indicated in the table or even slower than that. Moreover, we should not overlook the fact that reaching TRL6 or 7 does not automatically mean the system is going to reach full maturity. This point is proven by numerous programmes including two prominent laser programmes covered in this paper too, the ABL and the ATL. Furthermore, even when a system is at TRL8 or even 9 it may not deliver what the market needs and thus it will not be procured or deployed. An example of this in the DEW domain is the Active Denial System which was deployed but never used and later withdrawn from the field.

The case of Active Denial System brings us to the final point regarding factors affecting the proliferation of DEW, and that are the human made issues. The Delphi clearly indicated that human made factors were perceived to be the main cause for impeding the DEW coming of age. These worries covered legislative matters, health and safety issues, rules of engagement inflictions, fear for fratricide and general public scepticism. Since the first six factors were human made obstacles, this is a notion to be kept in mind as one assesses the entire picture.

Finally, when discussing the year DEWs will be in widespread use, we must not neglect availability questions. Currently, USA is the leading innovator in this area of technology. This also leads to the fact that she will have the sole right to the technology and thus can decide who and when it will sell it to. This changes the question from technological to political, and it is out of the scope of this research. Nonetheless, it is a variable that is assumed to have a major impact on the widespread use of DEW in the decades to come.

5.5. Answers to Research Questions

In this section, the answers to the research questions are presented together with a rationale behind them.

5.5.1. What are the Technologies and Systems under Development for AA and CRAM?

Based on the literature review this research identified 15 development programmes pursuing AA or CRAM capability. Of these 14 are laser systems and one is an HPRF system. These systems are presented in Table 36. No other directed energy technologies were involved in seeking for AA or CRAM systems.

Programme Name	Type	Purpose	Status	Goal
FEL (Free Electron Laser)	Free electron laser	Technology maturing programme	Early stage technology program MIT & Arizona state [2]	1MW+, 1 meter length,
DPAL (Diode Pumped Alkali Laser)	Gas laser	Strategic missile defence, ballistic missiles in boost phase	20-30kW, 20-30kg/kW	1MW+, 2kg/kW [38]
HELLADS (High Energy Liquid Laser Air Defense System) [61][31]	Liquid laser (Dye)	Air Force, A/G, self-protection	Developmental, entering field trials	150kW+, weight less than 5kg/kW
GBAD DE OTM (Ground Based Air Defence Directed Energy On The Move) [48]	Laser	Integration of several systems to one complete weapon system.	Field trials in 2017	UAS engagement capability for expeditionary forces (Marines). 30-50 kW.
HELE/LWM (High Energy Laser Effector/Laser Weapon Module) [54]	Laser	Rheinmetall's self-financed technology programme	Developmental, Demonstrator 3x10kW Successful engagement of UAV and RAM	
TLS (Tactical Laser System) [7]	Laser	Ship self-protection. UAS, light targets	10kW demonstrator in 2011.	
LDEW (Laser Directed Energy Weapon) [72]	Laser	UK MOD funded programme for a capability demonstrator	Started 1/2017	Demonstrator in 2019. Possibly leading to in service weapon in mid-2020.
Gamma [46]	Solid slab laser (SSL)	Northrop Grumman self-financed technology programme	Initial test in 2012 13,3kW units that can be combined	
HEL MD (High Energy Laser Mobile Demonstrator) [26]. Follow-on programme called HELMTT 105[53]	Solid slab laser (SSL)	Proof of principle for mobile GBAD DE for Army. HELMTT will use RELI's laser system.	successful test of 10kW	50-100kW. G-RAMM capability.
MLD (Maritime Laser Demonstrator) [47]	Solid slab laser (SSL)	Ship self-protection	Demonstrator utilizing JHPSSL in maritime conditions. 105kW in 2009.	No stated project goal. 300-600kW is considered achievable.
JHPSSL (Joint High Power Solid state Laser)	Solid slab laser (SSL)	Joint technology programme. Leveraged by Navy in MLD.	105kW in 2009.	
Excalibur	SSL/Fibre laser	Scalable multipurpose laser system for air vehicles (A/G, self-defence, missile defence	Developmental, demo in 2013	100kW+ [41]
LAWS (LAser Weapon System) [47]	SSL/Fibre laser	Ship self-protection	Prototype 30kW, installed on USS Ponce	100kW+ IOC stated for 2020-2021

Programme Name	Type	Purpose	Status	Goal
RELI (Robust Electric Laser Initiative) [69]	SSL/Fibre laser	Laser programme for US Army and Air Force operated platforms		Weight less than 7kg/kW, 30% wall-plug efficiency, 100kW+
HPM Demonstrator [29]0	HPRF	C-UAS	Engagement test in 2013. Successful downing of small UAVs.	Unknown.

Table 36: Ongoing Programmes Pursuing AA/CRAM Capability.

5.5.2. What is the Maturity Level of GBAD DEW in 2025-2030?

Only identified GBAD DEW systems were selected to answer this research question. All shipborne and airborne systems were also excluded as the research question is specifically about GBAD. Readers interested in other systems should refer to Table 35. Furthermore, some GBAD DEW systems were also excluded due to lack of adequate information to perform TRL assessment. In total seven systems were included, and the results are depicted in Table 37. The table includes columns for the current TRL assessment, predicted capability at TRL9, estimated time frame when the system reaches TRL9, and the assessed year when technology is commonly used according to the Delphi panel.

#	Programme Name	Technology	TRL 2017	Predicted capability in TRL9	Year for TRL9 based on TRL evolvement data	Year when in use based on Delphi
1	HPM Demonstrator [29]0	HPRF	7	Mobile C-UAS 2km	2021-2027	HPRF systems 2025-2030/ after 2035
2	HELE/LWM (High Energy Laser Effector/Laser Weapon Module) [54]	HEL	6/7	N/A	2023-2029	Laser systems 2030-2035
3	GBAD DE OTM (Ground Based Air Defence Directed Energy On The Move) [48]	Laser	6	Mobile C-UAS 3km	2023-2029	
4	RELI (Robust Electric Laser Initiative) [69][69]	SSL/Fibre laser	4/5	C-RAM/C-UAS 8km	2026-2032	
5	DPAL (Diode Pumped Alkali Laser)	Gas laser	4/5	Up to ballistic missile defence	2026-2032	
6	Gamma [46]	SSL laser	3/4	N/A	2029-2035	
7	FEL (Free Electron Laser)[2][33]0	FEL laser	2/3	Up to ballistic missile defence	2032-2037	

Table 37: Maturity of GBAD DEW in 2025-2030.

From the table, we can see that the three first systems (1-3) are the only systems which are likely to reach TRL9 by 2030. Systems 4 and 5 will only be mature by 2030 if a boost in the development process is witnessed. This may occur if the use of UAV’s increase drastically against US Forces. Systems 6 and 7 will not be TRL9 by 2030. It is also evident that the capability of GBAD DEW in 2025-2030 will be quite modest and mainly focused on countering UAV in short to mid ranges. As a summary in 2025-2030, there will be a maximum of three GBAD DEW systems in TRL9 who are capable of engaging UAVs in a distance of few kilometres.

5.5.3. What is the Applicability of DEW when Replacing or Developing Finland’s GBAD Capabilities after 2025?

The answer to this question is presented in a separate classified annexe which will not be made publicly available. It has been distributed to Army Command Finland and National Defence University. Finnish Defence Forces personnel with adequate security clearance can obtain reading rights to the document through regular procedures.

5.6. Limitations to Findings

The results introduced above incorporate certain limitations; firstly it needs to be appreciated that all the data and material are based on openly available public documents. An unclassified study which makes use of detailed information on a novel, defence related technology simply has to accept the fact that all the material is not accessible. It follows that some of the data is missing, some are equivocal and some may even be even misleading. This is the case although utmost attention was placed in verifying the data from multiple sources and by thoroughly assessing the integrity of the reference material.

As a consequence, while using the TRL calculator, there was a need to make some assumptions due to lack of verified information. This was because in many instances the metrics required by the calculator were precise and that level of granularity could not be found from publicly available articles. Hence inserted metrics are a combination of actual information from the literature and assessments made by the author. It is like any simulation; the results are based on the inserted metrics, and this is why the TRL levels indicated here should not be regarded as absolute facts. Nonetheless, utilising the calculator provided us with more justifiable and detailed information than what we would have gotten by merely placing the systems on the TRL scale based on the levels description shown in Table 2.

Furthermore, the forecasted TRL maturing timelines assume that progression and maturing occurs. It is vital to keep in mind that there are numerous reasons which may interfere with the maturing process and that not all systems ever will see TRL9, or they do but they still are not deployed.

Another limitation is the relatively small number of participants in the Delphi panel. Although nearly six months was used in first identifying and then attempting to persuade subject matter experts to participate, the number remained as low as 10. This does not mean that the validity of the Delphi is automatically compromised as the method relies specifically on the identification of subject matter experts. Nonetheless, a bigger panel would have made the results more solid.

6. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarises the main findings, presents the conclusions and makes recommendations for further work.

6.1. Research Aims

It was the intention of this thesis to utilise Delphi method and Technological Readiness Level (TRL) assessment supported by a literature review to answer the following research question and the supporting sub-questions:

- Research question: What is the applicability of directed energy weapons when replacing or developing Finland's GBAD capabilities after 2025?

- Sub-question 1: What are the DE technologies and systems under development for AA and CRAM? (SQ1)

- Sub-question 2: What is the maturity level of GBAD DEW in 2025-2030? (SQ2)

6.2. Summary of the Research

First, a literature review was conducted to establish the foundation of the researched topic, to aid in composing the Delphi questionnaires and most importantly to find an answer to sub-question 1. The literature review was followed by the application of both Delphi method and TRL assessment. Next, the results of both methods were compared and discussed. Moreover, finally, a synthesis of the results was constructed.

6.3. Literature Review

The main findings of the literature research were:

- The most prominent and mature DEW technologies today are High Energy Lasers (HEL) and High Power Radio Frequency Weapons (HPRF)
- Numerous ongoing programmes are developing HEL systems accompanied with a smaller number of HPRF programmes
- Both HEL and HPRF have a solid scientific foundation, and their utility as weapons have been researched for decades
- There are some functioning DEW demonstrators
- Despite the lengthy research and testing many obstacles remain to mature the technologies to the level where they could be deployed
- Output powers of current DEW are far from being adequate in engaging manned aircraft size targets

- Advantages of DEW include: Collateral damage reduction, Infinite magazine, low engagement price, beam travels at a speed of light, ability to engage multiple targets simultaneously and silence
- Disadvantages of DEW include: Size, weight and power (SWaP) issues, cooling related to excess heat, precision tracking requirements due to narrow beam, collateral damage and fratricide issues, need for a line of sight, limitations in range and weather related power losses

6.4. Delphi Method

A Delphi survey consisting three rounds was performed to find data to answer sub-question 2 “What is the maturity level of GBAD DEW in 2025-2030”. The survey included both classic and ranking type questions. It was revealed that, in this case, the classic type questions provided more converged answers than the ranking questions did. Based on the classic questions the Delphi panel’s opinion to the year when DEW’s will be commonly in use was established, and thus the method contributed in answering to sub-question 2. The main findings of the Delphi survey included:

- Laser weapon will be commonly used by the military in 2030
- Laser weapons will be mature enough for air defence in 2030-2035
- HPRF weapons will be commonly used by the military in 2025-2030
- HPRF weapons will be mature enough to be used for air defence in 2025-2030

6.5. TRL Assessment

TRL assessment was conducted to establish more valid and justifiable answers to sub-question 2. The idea was to have results based on another method to either validate or invalidate the Delphi results. The TRL assessment was executed by employing USAF TRL calculator using the data revealed by the literature review. After the current TRL’s of the DEW programmes were assessed, a forecast was made to identify the year of full maturity (TRL9). The main findings of the TRL assessment were:

- DEWs can engage UAV’s within 2-3km in 2021-2029
- DEWs can engage UAV’s within 10 km in 2024-2030
- DEWs can engage manned aircraft and possibly ballistic missiles from ranges exceeding 10 km in 2026-2037

6.6. Recommendations for Further Work

A number of recommendations are made for further work:

- The application and the findings should be reviewed by a panel accessible and able to provide classified information. This would ensure the use of current and detailed information regarding the actual maturity issues concerning DEW. Furthermore, this would provide valid information of the actual capability issues presented in the paper. Naturally, the research would have to be classified.

- A qualitative analysis of the attributes presented by the panel together with their ranking would provide a more insight of the obstacles forestalling the maturing of DEW. Based on this insight it would be possible to forecast the maturing of the DEW technology by building a technology roadmap encompassing the assessment of maturation timeline for individual segments of the particular system.

- The Delphi results should be elaborated by two alternative means. One is to include further rounds to seek enhanced consensus, especially in the ranked lists. The other one is to establish a new and/or larger panel. By doing this, we could witness actual consensus and validity to the results presented.

6.7. Concluding Statement

This research can answer the research questions. A thorough literature review showed that there are numerous DEW programmes and the scientific background is solid. The application of the methods revealed there that the maturing of DEWs would take some 5-15 years, depending on the target size and range. Furthermore, the results from the individual methods support each other and thus make them more valid.

7. REFERENCES

[1] Adamy Dave, (2015), *'Directed Energy Weapons- Part2: Supporting Technology',* The Journal of Electronic Defense, Issue 11, pp. 80-80

[2] Adamy Dave, (2015), *'Directed Energy Weapons- Part3: Military Lasers, continued',* The Journal of Electronic Defense, Issue 12, pp.82-84

[3] Adamy Dave, (2016), *'Directed Energy Weapons- Part5: HPRF Weapon Target Effects',* The Journal of Electronic Defense, Issue 2, pp. 44-46

[4] Amara, Roy (1981) *The Futures Field; How to Tell Good Work from Bad',* The Futurist. April 1981, Vol. 15, pp. 63-71.

[5] Amara, Roy (1991) *'Views on Futures Research Methodology',* Futures July-August, 1991, Vol. 23 Issue 6, pp. 645-650

[6] Babineau, Mark (2017), *'Mark Papineau's Linkedin profile'*, [Online]. Accessed 5.5.2017. https://www.linkedin.com/in/mark-babineau-8b97754a

[7] BAE Systems (2011), *'Successful Testing of the Mk83 Laser complete',* [Online]. Accessed 29.12.2016. http://www.baesystems.com/en/article/successful-testing-of-the-mk-38-laser-complete

[8] Baker, George H. (2011), *'High Power Electromagnetic Weapons: A Brief Tutorial'*, [Online]. Accessed 13.2.2017. https://works.bepress.com/george_h_baker/33/

[9] Banke, Jim (2015), *'Technology Readiness Levels Demystified',* NASA webpage [Online]. Accessed 16.1.2017. https://www.nasa.gov/topics/aeronautics/features/trl_demystified.html

[10] Boryung, Ju and Tao, Jin (2013), *'Incorporating Nonparametric Statistics into Delphi Studies in Library and Information Science'*, Information Research, Issue 3 [Online]. Accessed 25.1.2017. http://www.informationr.net/ir/18-3/paper589.html#.WIimTGWXC9u

[11] Brunderman, John A. (1999), *'High Power Radio Frequency Weapons: A Potential Counter to U.S. Stealth and Cruise Missile Technology'*, Air War College [Online]. Accessed 21.12.2016. http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA393362

[12] Campbell, John H. and Hayden, Joseph S. (2011), *'High-Power Solid-State Lasers: a Laser Glass Perspective'*, International Journal of Applied Glass Science, Issue. 2, pp. 1-28.

[13] Casey-Maslen, Stuart (2010), 'Non-kinetic-energy weapons termed 'non-lethal', Geneva, ADH.

[14] Coffey, Valerie C. (2014), *'New Advances in Defense Applications; High-Energy Lasers'*, Optics and Photinics News, Issue XX pp. 28-35.

[15] Dalkey, Norman C. (1968), *'Predicting the Future'*, Santa Monica, Rand Corporation.

[16] Dalkey, Norman C. (1969), '*The Delphi Method: an Experimental Study of Group Opinion*', Santa Monica, Rand Corporation.

[17] Defence IQ (2016), *'Is Directed Energy Really the Future of Weapon Systems?'* Defence IQ website [Online]. Accessed 7.2.2017. https://www.defenceiq.com/defence-technology/articles/is-directed-energy-really-the-future-of-weapon

[18] Domsch, Sebastian (2015), '*Laser Principle'*, [Online]. Accessed: 10.11.2016, www.umm.uni-heidelberg.de/.../basicoptics/2_LASER-SystemsI.pdf

[19] Ellis, Jason D. (2015), *'Directed Energy at the Crossroads'*, Washington D.C, Center for a New American Security.

[20] Ellis, Jason D. (2015), *'Directed-Energy Weapons: Promise and Prospects'*, Washington D.C, Center for a New American Security.

[21] European Commission (2016),*'Exploratory versus Normative Methods'*, [Online]. Accessed 5.7.2016, http://forlearn.jrc.ec.europa.eu/guide/4_methodology/meth_explo-norma.htm.

[22] European Space Agency (2008), 'Technology Readiness Levels Handbook for Space Applications', Paris, France.

[23] Ezekiel, Shaoul (2008), *'Understanding Lasers and Fiberoptics'*. [Online]. MIT OpenCourseWare, Accessed 11.11.2016. https://ocw.mit.edu.

[24] Fitzgerald, Ben and Sauler, Kelley (2014), *'Creative Disruption: Technology Strategy and the Future of the Global Defense Industry'*, Washington D.C, Center for a New American Security.

[25] Franken, P.A. and Sands, P.H. (eds.) (1959),*'The Ann Arbor Conference on Optical Pumping',*Ann Arbor, University of Michigan.

[26] Freedberger, Sydney J. jr.(2015), *'Army turns for Lockheed fo Alternative Laser'*, Breaking Defense [Online]. Accessed 29.12.2016. http://breakingdefense.com/2015/08/army-turns-to-lockheed-for-alternative-laser/

[27] Galdorisi George V. and Truver Scott C. (2010), *'The Zumwalt-Class Destroyer: A Technology "Bridge" Shaping the Navy after Next'*, Naval War College Review, Issue 3, pp. 63-72.

[28] Galdorisi, George (2016), *'A Potent One-Two Punch'*, U.S Naval Institute Proceedings, Issue 3, pp. 70-75.

[29] Giangreco, Leigh (2016*), 'Raytheon pitches CHAMP derivative for air defence'*, article in Flightglobal.com [Online]. Accessed 21.10.2016. https://www.flightglobal.com/news/articles/raytheon-pitches-champ-derivative-for-air-defence-426549/

[30] Glenn, Jerome C. and Gordon, Theodore J. (eds.) (2009) 'Futures Research Methodology 3.0', Washington D.C.: The Millennium Project.

[31] GlobalSecurity.org (2016), *'High Energy Liquid Laser Defense System',* [Online]. Accessed 2.5.2017. http://www.globalsecurity.org/military/systems/aircraft/systems/hellads.htm

[32] GlobalSecurity.org (2016), *'High-power microwave (HPM)/ E-Bomb',* [Online]. Accessed 2.5.2017. http://www.globalsecurity.org/military/systems/munitions/hpm.htm

[33] Gunzinger, Mark and Dougherty Chris (2012), *'Changing the Game; the Promise of Directed-Energy Weapons'*, Washington D.C, Center for Strategic and Budgetary Assessments.

[34] Helmer, Olaf (1967), *'Analysis of the Future: The Delphi Method'*, Santa Monica, Rand Corporation.

[35] Kobus, Jörn and Westner, Markus (2016), *'Ranking-type Delphi Studies in IS Research: Step-by-step Guide and Analytical Extension',* Conference paper presented in IADIS International Conference in Information Systems 2016 [Online]. Accessed 25.1.2017. goo.gl/BbSMko

[36] Lawrence Livermore National Laboratory webpage (2017), *'Diode-Pumped Alkali Laser: A New Combination'*, [Online]. Accessed 3.5.2017

[37] Legendre, Pierre (2010), Coefficient of Concordance. In Salkind, N.J. Ed. *'Encyclopedia of Research Design'* 1st ed. Los Angeles, SAGE Publications Inc.

[38] Lewis, George (2016), *'Chronology of MDA's Plans for Laser Boost-Phase Defense'* [Online]. Accessed 29.12.2016. https://mostlymissiledefense.com/2016/08/26/chronology-of-mdas-plans-for-laser-boost-phase-defense-august-26-2016/

[39] Lorenser, Dirk (2009), *'Lasers; an Application-oriented Overview of the Current State-of-the-art in Industry and Research'*, [Online] at: http://www.slideshare.net/dlorenser/part-i-laser-basics-lorenser-2009. Accessed: 10.11.2016.

[40] Malenic, Marina (2016), *‘Raytheon counter-UAV electronic attack demonstrator garners DoD interest’*, Jane’s Defence Weekly online article [Online]. Accessed 21.10.2016. http://www.janes.com/article/61709/raytheon-counter-uav-electronic-attack-demonstrator-garners-dod-interest

[41] Mangano, Joseph (2016), *‘Excalibur’,* Defense Advanced Research Projects Agency [Online]. Accessed 5.7.2016,http://www.darpa.mil/program/excalibur

[42] Moran, Stuart (2012), ‘Historical Overview of Directed-Energy Work at Dahlgren’, Leading Edge, Issue 4, pp. 12-25.

[43] National Academy of Sciences (2003), *‘Technology Development for Army Unmanned Ground Vehicles’*, Washington D.C., The National Academies Press.

[44] Nolte, Peter, Apffelstaedt, Arno and Gollnick, Volker (2012), *‘Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency’*, Proceedings of the Third International Air Transport and Operations Symposium 2012.

[45] Nolte, William L., Kennedy, Brian C. and Dziegiel Roger J. jr (2003), ‘*Technology Readiness Calculator’*, White Paper, Air Force Research Laboratory [Online]. Accessed 16.1.2017 www.dtic.mil/ndia/2003systems/nolte2.pdf

[46] Northrop Grumman Corporation webpage (2016), *‘Gamma’*, [Online]. Accessed 21.7.2016. http://www.northropgrumman.com/Capabilities/SolidStateHighEnergyLaserSystems/Pages/Gamma.aspx

[47] O’Rourke, Ronald (2015), *‘Navy Shipboard Lasers for Surface, Air and Missile Defense: Background and Issues for Congress’* Washington D.C. Congressional Research Service. [Online]. Accessed 29.12.2016. https://fas.org/sgp/crs/weapons/R41526.pdf

[48] Office of the Naval Research (2016), *‘Ground Based Air Defense on the Move’* [Online]. Accessed 29.12.2016. https://www.onr.navy.mil/Media-Center/Fact-Sheets/GBAD.aspx

[49] Okoli, Chitu and Pawlowski, Suzanne D. (2004), *‘The Delphi method as a research tool: an example, design considerations and applications*, Information & Management, Issue. 42, pp. 15-29.

[50] Oppenheimer, Andy (2015), *‘Zapping the Target: High-Energy Laser Weapons Come of Age’*, Military Technology, Issue 9, pp. 106-109.

[51] Paschotta, Rudiger (2008). *’Encyclopedia of Laser Physics and Technology’*, Hoboken NJ, Wiley.

[52] Paul, Donald J. (2002), *‘Stimulated Emission’*, University of Glasgow website [Online]. Accessed 19.1.2017. http://userweb.eng.gla.ac.uk/douglas.paul/QCL/stimulated.html

[53] Peck, Michael (2016), *‘High-energy laser weapons target UAVs’*, C4ISRNET- webpage [Online]. Accessed 21.12.2016. http://www.c4isrnet.com/story/military-tech/show-reporter/afcea-west/2016/02/18/navys-intel-chief-battling-clearance-controversy-cyber-struggles/80574736/

[54] Rheinmetall Group (2016),*’ The high-energy laser: Weapon of the future already a reality at Rheinmetall’*, [Online]. Accessed 28.12.2016, http://www.rheinmetall.com/en/rheinmetall_ag/press/themen_im_fokus/zukunftswaffe_hel/

[55] Roberts, Edward B. (1969) *’Exploratory and Normative Technological Forecasting; a Critical Appraisal’*, Technological Forecasting Vol. 1 Issue 2 pp. 113-127.

[56] Sackman, H. (1974), ‘Delphi Assessment: Exper Opinion, Forecasting, and Group Process’, Santa Monica, Rand Corporation.

[57] Schlerer, Curtis D. (1999), *‘Electronic Warfare in the Information Age’*, Boston, Artech House.

[58] Schmidt, Roy C. (1997), *‘Managing Delphi Surveys Using Nonparametric Statistical Techniques’*, Decision Sciences, Vol. 28 Issue 3, pp. 763-774.

[59] Seckel, Scott (2015), *‘Physics and Biodesign professor is shrinking electron-laser technology’*, Arizona State University webpage [Online]. Accessed 21.12.2016. https://asunow.asu.edu/20151013-graves-compact-free-electron-laser

[60] Seffers, George I. (2016), *‘CHAMP Prepares for Future Fights’*, Signal Online Magazine [Online]. Accessed 21.12.2016. http://www.afcea.org/content/?q=Article-champ-prepares-future-fights

[61] Shaver, David (2016), *‘High Energy Liquid Laser Area Defense System’,* Defense Advanced Research Projects Agency [Online]. Accessed 29.12.2016. http://www.darpa.mil/program/high-energy-liquid-laser-area-defense-system

[62] Siegel, Sidney and Castellan, John, N. Jr. (1988) *‘Nonparametric Statistics for the Behavioral Sciences’* 2nd Edition, Singapore: McGraw-Hill Book Co.

[63] Skulmoski, Gregory J., Hartman Francis T. and Krahn Jennifer (2007), *’The Delphi Method for Graduate Research’*, Journal of Information Technology Education pp. 1-21

[64] Stevenson, Angus and Waite, Maurice, eds. (2011), *‘Concise Oxford English Dictionary’*, 12th edition, Oxford, Oxford University Press.

[65] Stoudt, David C. (2012), ‘Naval Directed-Energy Weapons – No Longer a Future Concept’, Leading Edge, Issue 4, pp. 6-11.

[66] Sullivan, Michael III (2010), ‘Statistics: Informed Decisions Using Data’, Pearson.

[67] Syring, James (2016) *‘Ballistic Missile Defense System Update’*, Presentation at the Center for Strategic and International Studies, January 20, 2016. [Online]. Accessed 21.12.2016. *https://www.c-span.org/video/?403405-1/discussion-ballistic-missile-defense*.

[68] Tidd, Joe and Bessant, John (2016), *’Technological forecasting’* Innovation Portal [Online] Accessed 5.7.2016, http://www.innovation-portal.info/toolkits/technological-forecasting/.

[69] U.S Army Space and Missile Defense Command (2014), *‘Robust Electric Laser Initiative’,* [Online]. Accessed 29.12.2016. www.smdc.army.mil/FactSheets/RELI.pdf

[70] United Kingdom Ministry of Defence (2017), *‘SRL Self Assessment Tool’,* Acquisition System Guidance [Online]. Accessed 21.2.2017. https://www.aof.mod.uk/aofcontent/tactical/techman/content/srl_howtoselfassess.htm

[71] United Kingdom Ministry of Defence (2017), *‘Technology Readiness Levels’*, Acquisition System Guidance [Online]. Accessed 21.2.2017. https://www.aof.mod.uk/aofcontent/tactical/techman/content/trl_whatarethey.htm

[72] United Kingdom Ministry of Defence (2017), *‘UK Innovation: Laser Weapon Contract Awarded’* [Online]. Accessed 16.1.2017. https://www.gov.uk/government/news/uk-innovation-laser-weapon-contract-awarded

[73] United States Department of Defense (2010), *‘Defense Acquisition Guidebook’*, Washington D.C.

[74] United States Department of Defense (2011), *‘Technology Readiness Assessment (TRA) Guidance’*, Washington D.C.

[75] United States Department of Defense (2016), ‘Joint Publication 1-02: Dictionary of Military and Associated Terms’, Washington D.C.

[76] United States Department of Energy (2011), *‘Technology Readiness Assessment Guide’*, Washington D.C.

[77] United States Naval Academy (2016), ’Fundamentals of Naval Weapons Systems’ [Online]. Accessed 14.4.2016. https://fas.org/man/dod-101/navy/docs/fun/

[78] US Air Force Research Laboratory (20XX), *‘AFRL TRL Calculator Version 2.2’*, [Online]. Accessed 21.2.2017. aries.ucsd.edu/ARIES/.../0712/.../TRL%20Calc%20Ver%202_2.xls

[79] Weinberger, Sharon (2012), *‘High-Power Microwave Weapons Start to Look Like Dead-End’*, Scientific American [Online]. Accessed 21.12.2016https://www.scientificamerican.com/article/high-power-microwave-weapons-start-to-look-like-dead-end/

[80] Wells, Herbert G. (1988), *‘The War of the Worlds’,* New York, Bantam Classic Edition.

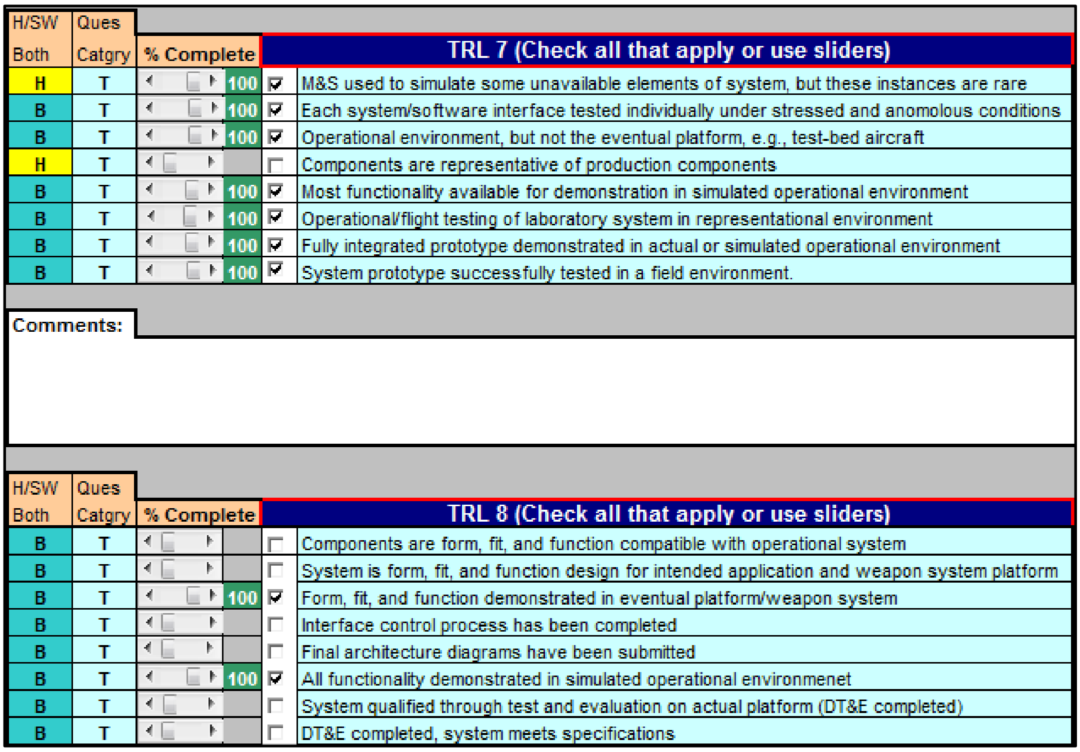
[81] Wingenbach, Karl E. and Lisenbee, Donald G. jr. (2007), *‘Deconfusing Lethal and Kinetic Terms’*, Joint Forces Quarterly, Issue 46, pp. 8-9.

[82] Worrell, James L., Di Gangi, Paul M. and Bush, Ashley A. (2013), *‘Exploring the use of Delphi Method in accounting information systems research’*, International Journal of Accounting Information Systems, Issue 14, pp. 193-208.

[83] Zaiontz, Charles (2013), *’Kendall’s coefficient of concordance’*, Real Statistics Using Excel [Online]. Accessed 21.12.2016. http://www.real-statistics.com/reliability/kendalls-w/

8. APPENDICES

8.1. Inserted Values and Results of TRL Calculator

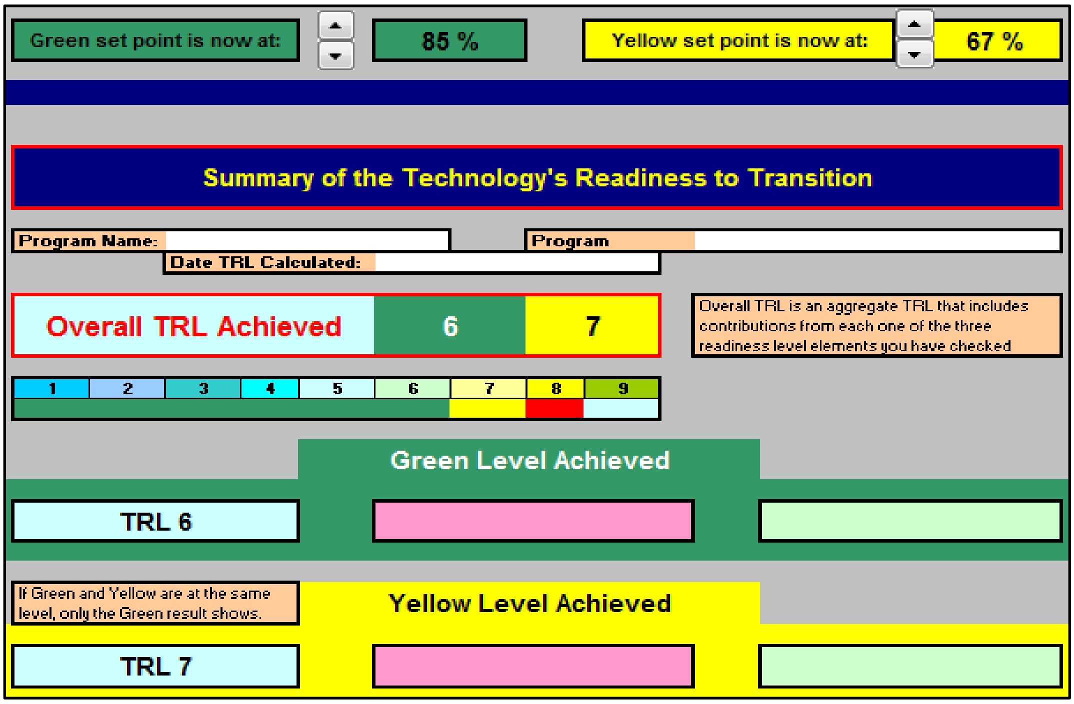


H/SW Both	Ques Catgry	% Complete	TRL 7 (Check all that apply or use sliders)
H	T	100	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T	100	Each system/software interface tested individually under stressed and anomolous conditions
B	T	100	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T		Components are representative of production components
B	T	100	Most functionality available for demonstration in simulated operational environment
B	T	100	Operational/flight testing of laboratory system in representational environment
B	T	100	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T	100	System prototype successfully tested in a field environment.

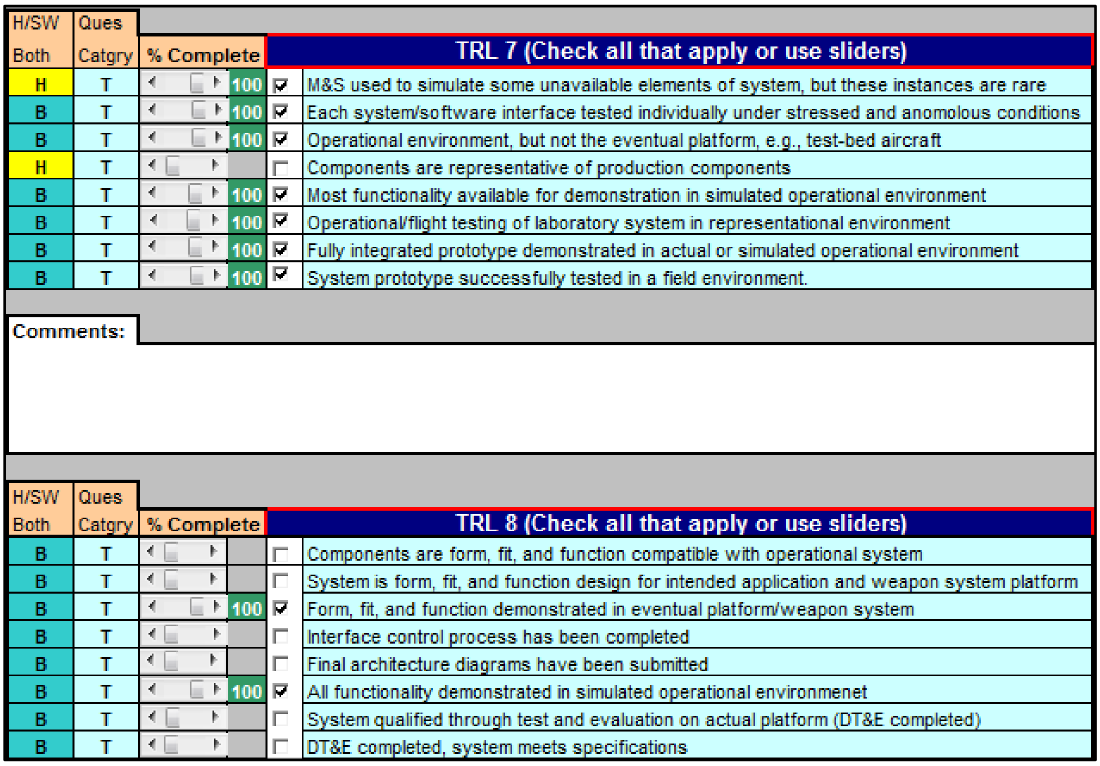
Comments:

H/SW Both	Ques Catgry	% Complete	TRL 8 (Check all that apply or use sliders)
B	T		Components are form, fit, and function compatible with operational system
B	T		System is form, fit, and function design for intended application and weapon system platform
B	T	100	Form, fit, and function demonstrated in eventual platform/weapon system
B	T		Interface control process has been completed
B	T		Final architecture diagrams have been submitted
B	T	100	All functionality demonstrated in simulated operational environmenet
B	T		System qualified through test and evaluation on actual platform (DT&E completed)
B	T		DT&E completed, system meets specifications

Inserted Values ABL



TRL Results ABL

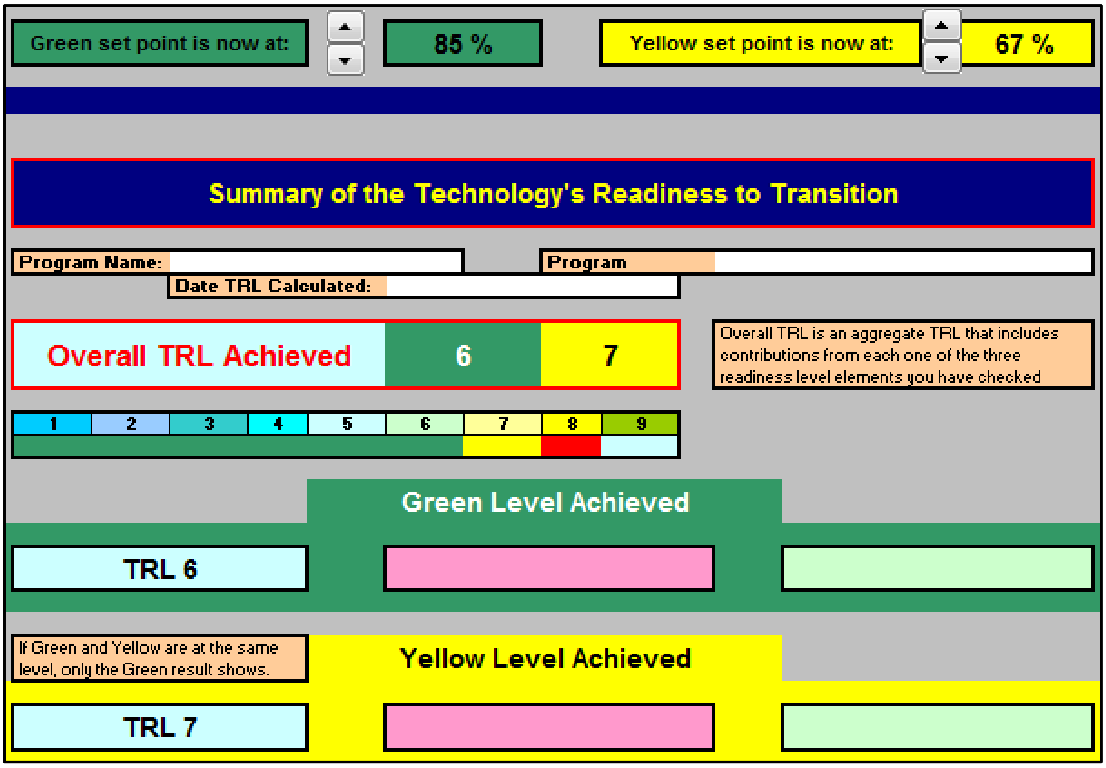


H/SW Both	Ques Catgry	% Complete		TRL 7 (Check all that apply or use sliders)
H	T	100	☑	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T	100	☑	Each system/software interface tested individually under stressed and anomolous conditions
B	T	100	☑	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T		☐	Components are representative of production components
B	T	100	☑	Most functionality available for demonstration in simulated operational environment
B	T	100	☑	Operational/flight testing of laboratory system in representational environment
B	T	100	☑	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T	100	☑	System prototype successfully tested in a field environment.

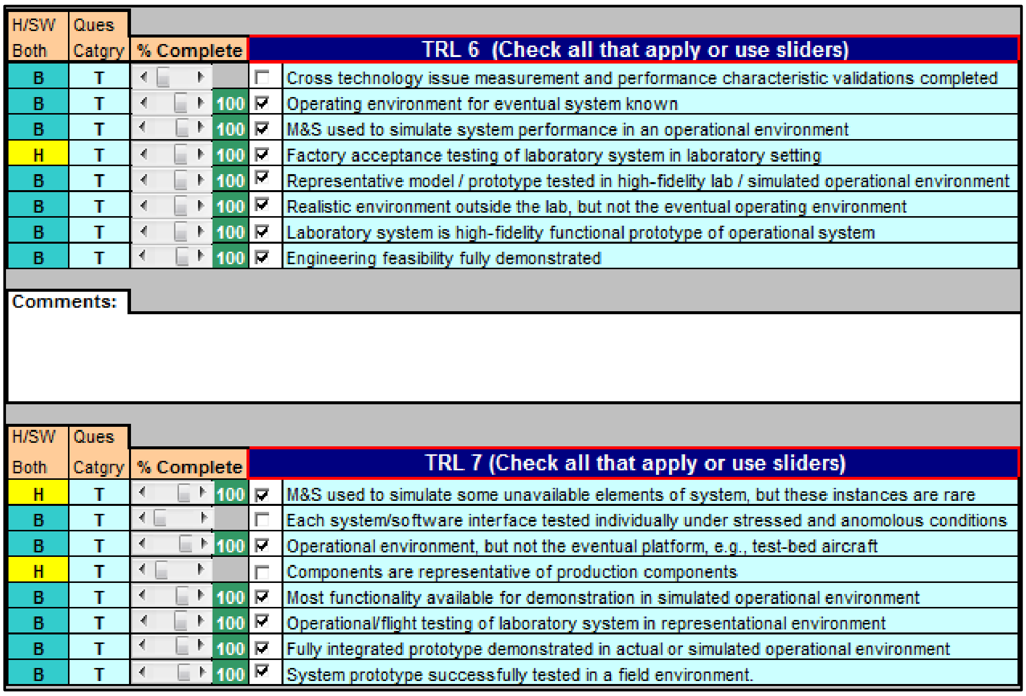
Comments:

H/SW Both	Ques Catgry	% Complete		TRL 8 (Check all that apply or use sliders)
B	T		☐	Components are form, fit, and function compatible with operational system
B	T		☐	System is form, fit, and function design for intended application and weapon system platform
B	T	100	☑	Form, fit, and function demonstrated in eventual platform/weapon system
B	T		☐	Interface control process has been completed
B	T		☐	Final architecture diagrams have been submitted
B	T	100	☑	All functionality demonstrated in simulated operational environmenet
B	T		☐	System qualified through test and evaluation on actual platform (DT&E completed)
B	T		☐	DT&E completed, system meets specifications

Inserted Values ATL



TRL Results ATL

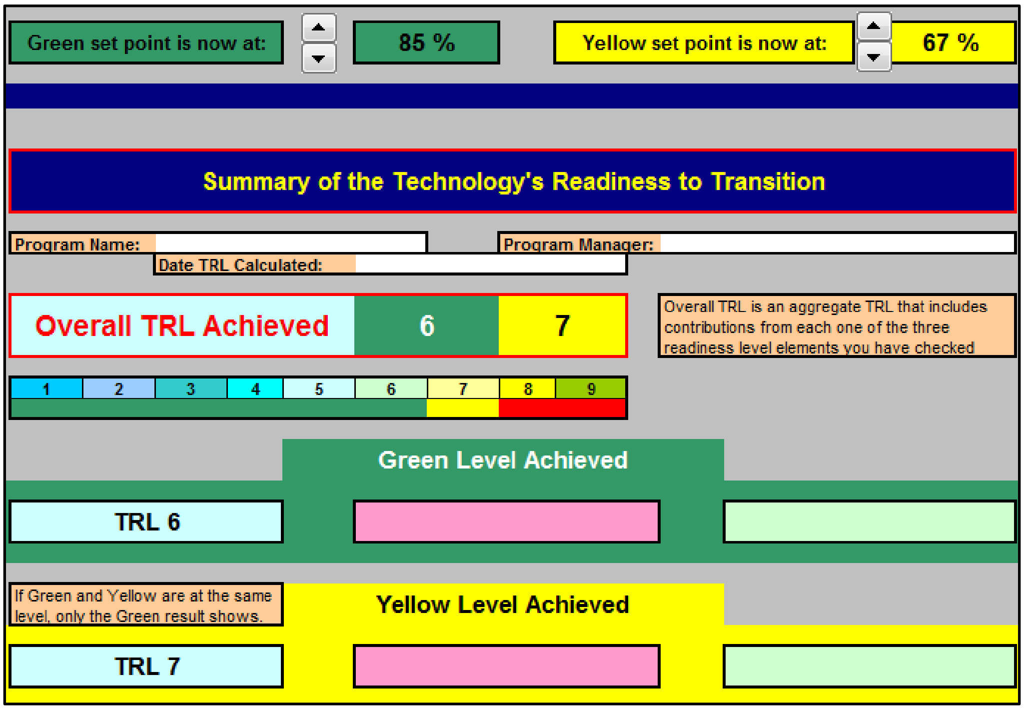


H/SW Both	Ques Catgry	% Complete		TRL 6 (Check all that apply or use sliders)
B	T		☐	Cross technology issue measurement and performance characteristic validations completed
B	T	100	☑	Operating environment for eventual system known
B	T	100	☑	M&S used to simulate system performance in an operational environment
H	T	100	☑	Factory acceptance testing of laboratory system in laboratory setting
B	T	100	☑	Representative model / prototype tested in high-fidelity lab / simulated operational environment
B	T	100	☑	Realistic environment outside the lab, but not the eventual operating environment
B	T	100	☑	Laboratory system is high-fidelity functional prototype of operational system
B	T	100	☑	Engineering feasibility fully demonstrated

Comments:

H/SW Both	Ques Catgry	% Complete		TRL 7 (Check all that apply or use sliders)
H	T	100	☑	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T		☐	Each system/software interface tested individually under stressed and anomolous conditions
B	T	100	☑	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T		☐	Components are representative of production components
B	T	100	☑	Most functionality available for demonstration in simulated operational environment
B	T	100	☑	Operational/flight testing of laboratory system in representational environment
B	T	100	☑	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T	100	☑	System prototype successfully tested in a field environment.

Inserted Values CHAMP



TRL Results CHAMP

H/SW Both	Ques Catgry	% Complete		TRL 4 (Check all that apply or use slider for % complete)
B	T	100	☑	Cross technology issues (if any) have been fully identified
H	T	100	☑	Individual components tested in laboratory/by supplier (contractor's component acceptance tes
H	T	100	☑	M&S used to simulate some components and interfaces between components
B	T		☐	Overall system requirements for end user's application are known
H	T	100	☑	Laboratory experiments with available components show that they work together (lab kludge)
H	T	100	☑	Hardware in the loop/computer in the loop tools to establish component compatibility
B	T	100	☑	Technology demonstrates basic functionality in simplified environment
B	T	100	☑	Controlled laboratory environment
B	T	100	☑	Low fidelity technology "system" integration and engineering completed in a lab environment
B	T	100	☑	Functional work breakdown structure developed

Comments:

H/SW Both	Ques Catgry	% Complete		TRL 5 (Check all that apply or use sliders)
B	T	100	☑	Cross technology effects (if any) identified and established through analysis
B	T		☐	System interface requirements known
B	T	100	☑	Interfaces between components/subsystems are realistic (Breadboard with realistic interfaces
B	T	100	☑	High fidelity lab integration of system completed, ready for test in realistic/simulated environmen
H	T	100	☑	Fidelity of system mock-up improves from breadboard to brassboard
B	T		☐	Laboratory environment modified to approximate operational environment
B	T	100	☑	IPT develops requirements matrix with thresholds and objectives
B	T	100	☑	Physical work breakdown structure available

Inserted Values DPAL

Green set point is now at: 85 %

Yellow set point is now at: 67 %

Summary of the Technology's Readiness to Transition

Program Name:

Program

Date TRL Calculated:

Overall TRL Achieved	4	5

Overall TRL is an aggregate TRL that includes contributions from each one of the three readiness level elements you have checked

1	2	3	4	5	6	7	8	9

Green Level Achieved

TRL 4

If Green and Yellow are at the same level, only the Green result shows.

Yellow Level Achieved

TRL 5

TRL Results DPAL

H/SW Both	Ques Catgry	% Complete		Do you want to assume completion of TRL 2? — TRL 2 (Check all that apply or use slider for % complete)
B	T	100	☑	Potential system or component application(s) have been identified
B	T	100	☑	Paper studies show that application is feasible
B	T	100	☑	An apparent theoretical or empirical design solution identified
H	T	100	☑	Basic elements of technology have been identified
B	T	100	☑	Desktop environment
H	T	100	☑	Components of technology have been partially characterized
H	T	100	☑	Performance predictions made for each element
B	T	100	☑	Initial analysis shows what major functions need to be done
H	T	100	☑	Modeling & Simulation only used to verify physical principles
B	T	100	☑	Rigorous analytical studies confirm basic principles
B	T	100	☑	Individual parts of the technology work (No real attempt at integration)
B	T	100	☑	Know what output devices are available
B	T	100	☑	Know what experiments you need to do (research approach)

Comments:

H/SW Both	Ques Catgry	% Complete		Do you want to assume completion of TRL 3? — TRL 3 (Check all that apply or use slider for % complete)
B	T	100	☑	Academic environment
H	T	100	☑	Predictions of elements of technology capability validated by Analytical Studies
H	T	100	☑	Science known to extent that mathematical and/or computer models and simulations are possi
H	T	100	☑	Predictions of elements of technology capability validated by Modeling and Simulation
B	T	100	☑	Laboratory experiments verify feasibility of application
H	T		☐	Predictions of elements of technology capability validated by Laboratory Experiments
B	T		☐	Cross technology effects (if any) have begun to be identified
B	T	100	☑	Paper studies indicate that system components ought to work together
B	T		☐	Metrics established
B	T	100	☑	Scientific feasibility fully demonstrated
B	T	100	☑	Analysis of present state of the art shows that technology fills a need

Inserted Values FEL

Green set point is now at: 85 %

Yellow set point is now at: 67 %

Summary of the Technology's Readiness to Transition

Program Name:

Program

Date TRL Calculated:

Overall TRL Achieved	2	3

Overall TRL is an aggregate TRL that includes contributions from each one of the three readiness level elements you have checked

1	2	3	4	5	6	7	8	9

Green Level Achieved

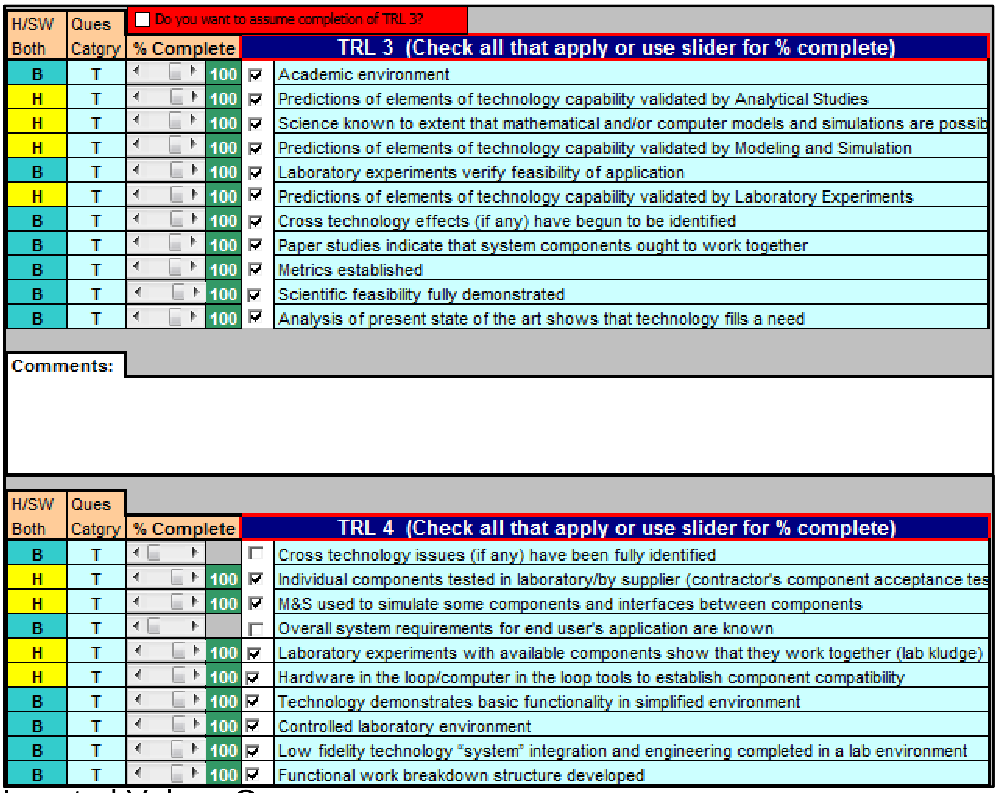
TRL 2

If Green and Yellow are at the same level, only the Green result shows.

Yellow Level Achieved

TRL 3

TRL Results FEL



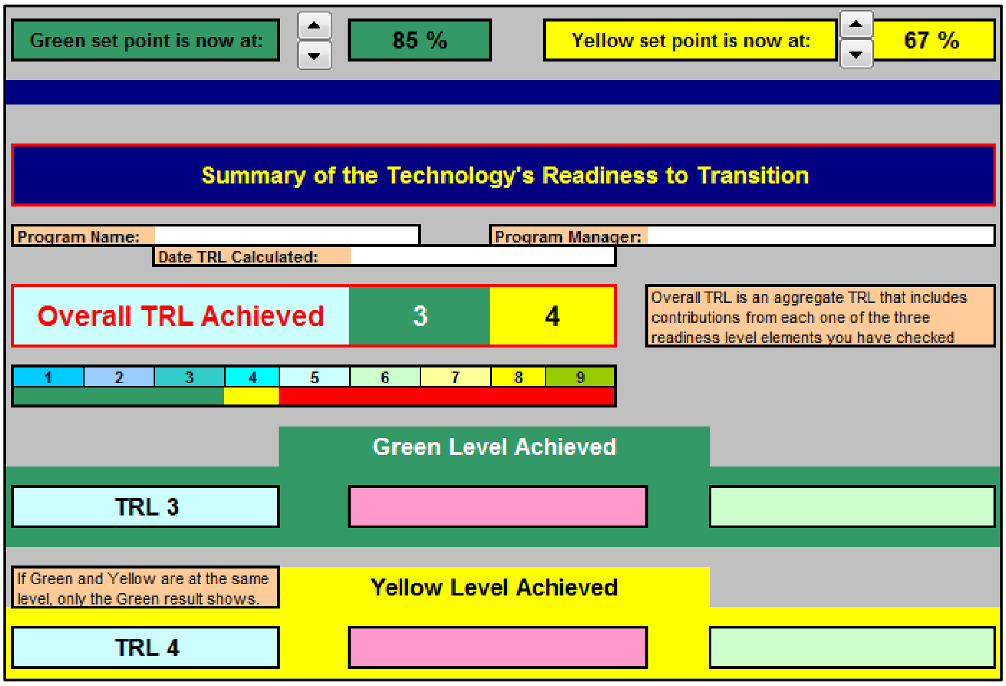
Do you want to assume completion of TRL 3?

H/SW Both	Ques Catgry	% Complete		TRL 3 (Check all that apply or use slider for % complete)
B	T	100	☑	Academic environment
H	T	100	☑	Predictions of elements of technology capability validated by Analytical Studies
H	T	100	☑	Science known to extent that mathematical and/or computer models and simulations are possib
H	T	100	☑	Predictions of elements of technology capability validated by Modeling and Simulation
B	T	100	☑	Laboratory experiments verify feasibility of application
H	T	100	☑	Predictions of elements of technology capability validated by Laboratory Experiments
B	T	100	☑	Cross technology effects (if any) have begun to be identified
B	T	100	☑	Paper studies indicate that system components ought to work together
B	T	100	☑	Metrics established
B	T	100	☑	Scientific feasibility fully demonstrated
B	T	100	☑	Analysis of present state of the art shows that technology fills a need

Comments:

H/SW Both	Ques Catgry	% Complete		TRL 4 (Check all that apply or use slider for % complete)
B	T		☐	Cross technology issues (if any) have been fully identified
H	T	100	☑	Individual components tested in laboratory/by supplier (contractor's component acceptance tes
H	T	100	☑	M&S used to simulate some components and interfaces between components
B	T		☐	Overall system requirements for end user's application are known
H	T	100	☑	Laboratory experiments with available components show that they work together (lab kludge)
H	T	100	☑	Hardware in the loop/computer in the loop tools to establish component compatibility
B	T	100	☑	Technology demonstrates basic functionality in simplified environment
B	T	100	☑	Controlled laboratory environment
B	T	100	☑	Low fidelity technology "system" integration and engineering completed in a lab environment
B	T	100	☑	Functional work breakdown structure developed

Inserted Values Gamma



TRL Results Gamma

H/SW Both	Ques Catgry	% Complete		TRL 6 (Check all that apply or use sliders)
B	T		[ ]	Cross technology issue measurement and performance characteristic validations completed
B	T	100	[x]	Operating environment for eventual system known
B	T	100	[x]	M&S used to simulate system performance in an operational environment
H	T	100	[x]	Factory acceptance testing of laboratory system in laboratory setting
B	T	100	[x]	Representative model / prototype tested in high-fidelity lab / simulated operational environment
B	T	100	[x]	Realistic environment outside the lab, but not the eventual operating environment
B	T	100	[x]	Laboratory system is high-fidelity functional prototype of operational system
B	T	100	[x]	Engineering feasibility fully demonstrated

Comments:

H/SW Both	Ques Catgry	% Complete		TRL 7 (Check all that apply or use sliders)
H	T	100	[x]	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T		[ ]	Each system/software interface tested individually under stressed and anomolous conditions
B	T	100	[x]	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T		[ ]	Components are representative of production components
B	T	100	[x]	Most functionality available for demonstration in simulated operational environment
B	T	100	[x]	Operational/flight testing of laboratory system in representational environment
B	T	100	[x]	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T		[ ]	System prototype successfully tested in a field environment.

Inserted Values GBAD DE OTM

Green set point is now at: 85 %

Yellow set point is now at: 67 %

Summary of the Technology's Readiness to Transition

Program Name:

Program Manager:

Date TRL Calculated:

Overall TRL Achieved 6

Overall TRL is an aggregate TRL that includes contributions from each one of the three readiness level elements you have checked

1	2	3	4	5	6	7	8	9

Green Level Achieved

TRL 6

If Green and Yellow are at the same level, only the Green result shows.

Yellow Level Achieved

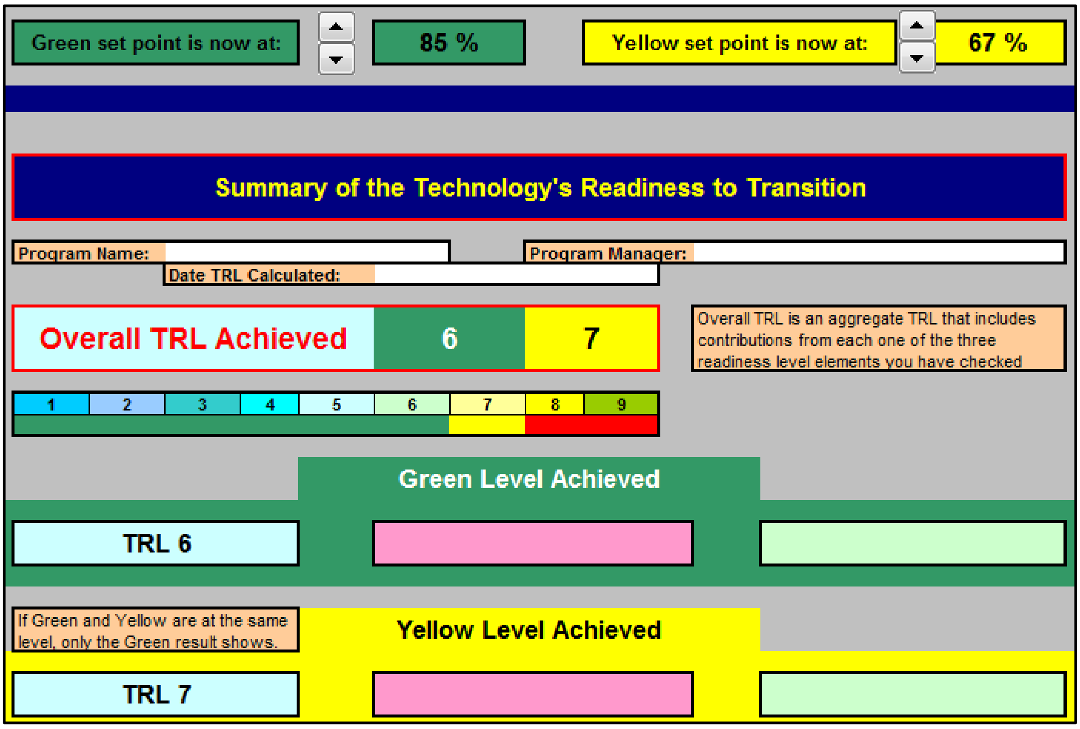
TRL Results GBAD DE OTM

H/SW Both	Ques Catgry	% Complete		TRL 6 (Check all that apply or use sliders)
B	T		☐	Cross technology issue measurement and performance characteristic validations completed
B	T	100	☑	Operating environment for eventual system known
B	T	100	☑	M&S used to simulate system performance in an operational environment
H	T	100	☑	Factory acceptance testing of laboratory system in laboratory setting
B	T	100	☑	Representative model / prototype tested in high-fidelity lab / simulated operational environment
B	T	100	☑	Realistic environment outside the lab, but not the eventual operating environment
B	T	100	☑	Laboratory system is high-fidelity functional prototype of operational system
B	T	100	☑	Engineering feasibility fully demonstrated

Comments:

H/SW Both	Ques Catgry	% Complete		TRL 7 (Check all that apply or use sliders)
H	T	100	☑	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T		☐	Each system/software interface tested individually under stressed and anomolous conditions
B	T	100	☑	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T		☐	Components are representative of production components
B	T	100	☑	Most functionality available for demonstration in simulated operational environment
B	T	100	☑	Operational/flight testing of laboratory system in representational environment
B	T	100	☑	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T	100	☑	System prototype successfully tested in a field environment.

Inserted Values GBAD DE OTM



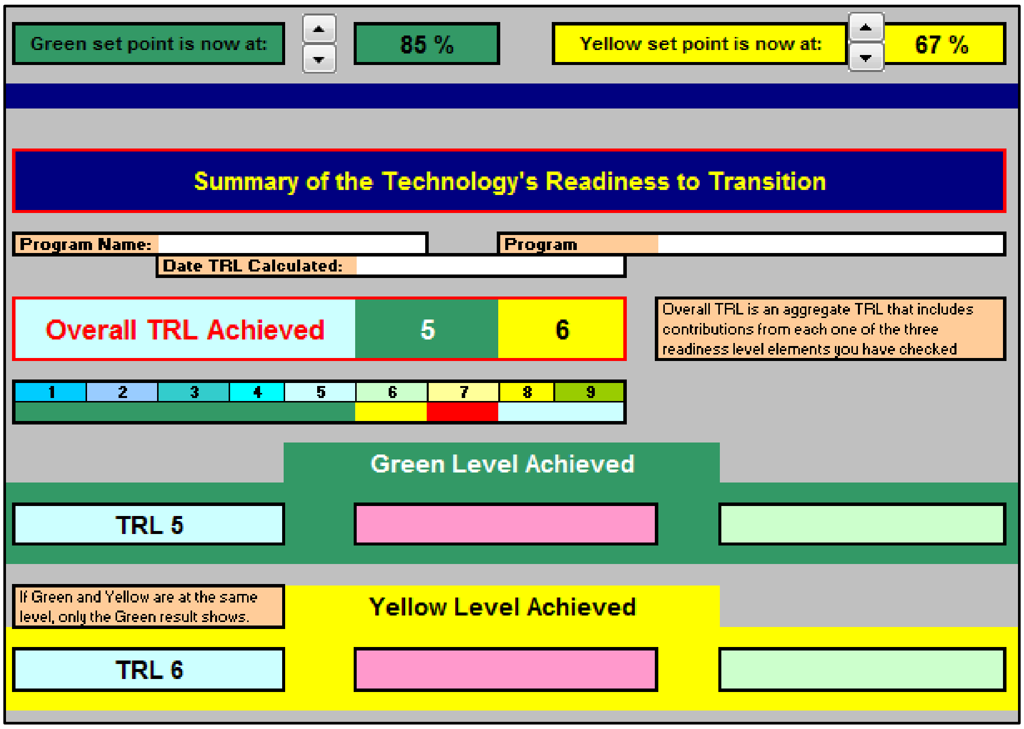
TRL Results HELE/LWM

H/SW Both	Ques Catgry	% Complete		TRL 6 (Check all that apply or use sliders)
B	T	100	☑	Cross technology issue measurement and performance characteristic validations completed
B	T		☐	Operating environment for eventual system known
B	T	100	☑	M&S used to simulate system performance in an operational environment
H	T	100	☑	Factory acceptance testing of laboratory system in laboratory setting
B	T	100	☑	Representative model / prototype tested in high-fidelity lab / simulated operational environment
B	T	100	☑	Realistic environment outside the lab, but not the eventual operating environment
B	T	100	☑	Laboratory system is high-fidelity functional prototype of operational system
B	T		☐	Engineering feasibility fully demonstrated

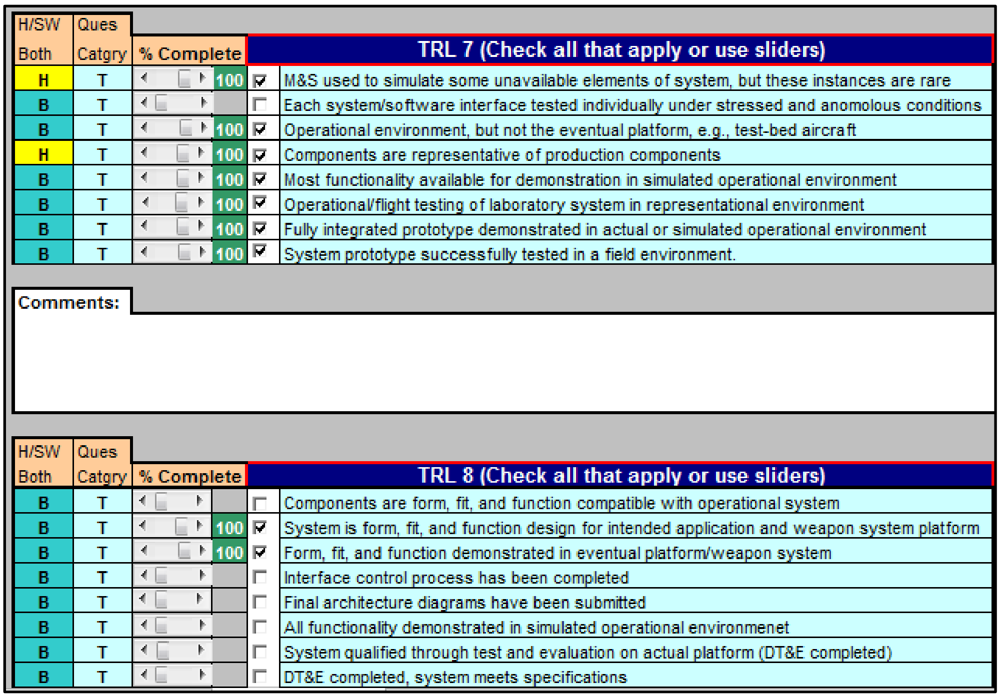
Comments:

H/SW Both	Ques Catgry	% Complete		TRL 7 (Check all that apply or use sliders)
H	T	100	☑	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T	100	☑	Each system/software interface tested individually under stressed and anomolous conditions
B	T		☐	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T		☐	Components are representative of production components
B	T	100	☑	Most functionality available for demonstration in simulated operational environment
B	T	100	☑	Operational/flight testing of laboratory system in representational environment
B	T		☐	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T		☐	System prototype successfully tested in a field environment.

Inserted Values HELLADS



TRL Results HELLADS

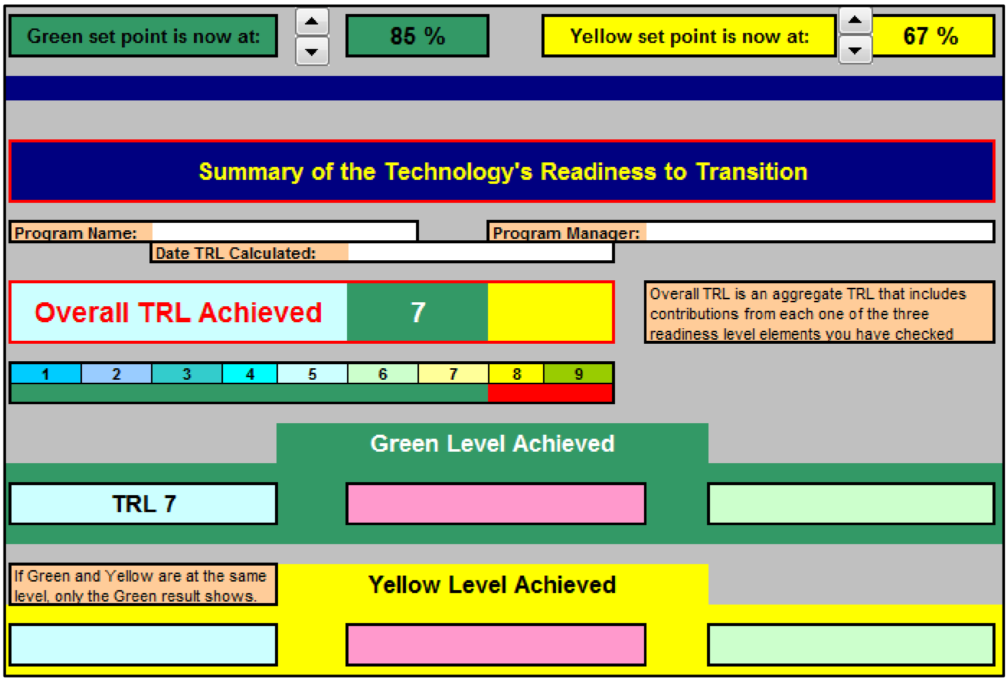


H/SW Both	Ques Catgry	% Complete		TRL 7 (Check all that apply or use sliders)
H	T	100	☑	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T		☐	Each system/software interface tested individually under stressed and anomolous conditions
B	T	100	☑	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T	100	☑	Components are representative of production components
B	T	100	☑	Most functionality available for demonstration in simulated operational environment
B	T	100	☑	Operational/flight testing of laboratory system in representational environment
B	T	100	☑	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T	100	☑	System prototype successfully tested in a field environment.

Comments:

H/SW Both	Ques Catgry	% Complete		TRL 8 (Check all that apply or use sliders)
B	T		☐	Components are form, fit, and function compatible with operational system
B	T	100	☑	System is form, fit, and function design for intended application and weapon system platform
B	T	100	☑	Form, fit, and function demonstrated in eventual platform/weapon system
B	T		☐	Interface control process has been completed
B	T		☐	Final architecture diagrams have been submitted
B	T		☐	All functionality demonstrated in simulated operational environmenet
B	T		☐	System qualified through test and evaluation on actual platform (DT&E completed)
B	T		☐	DT&E completed, system meets specifications

Inserted Values HPM Demonstrator



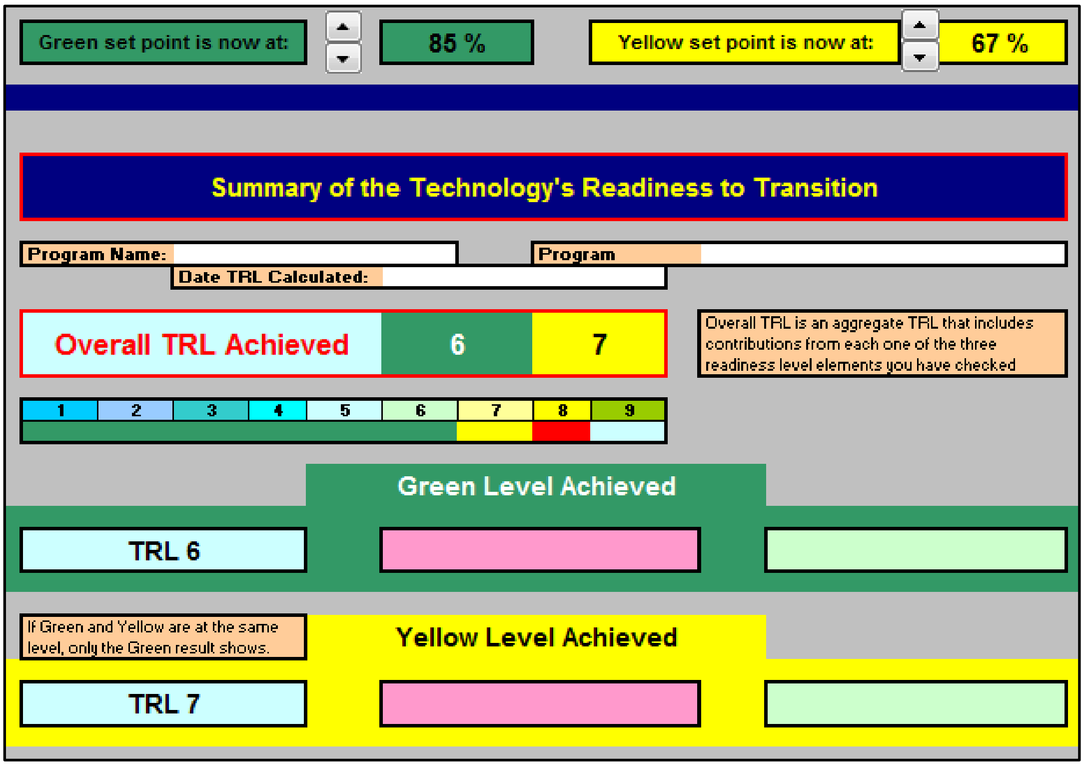
TRL Results HPM Demonstrator

H/SW Both	Ques Catgry	% Complete		TRL 6 (Check all that apply or use sliders)
B	T	100	☑	Cross technology issue measurement and performance characteristic validations completed
B	T	100	☑	Operating environment for eventual system known
B	T	100	☑	M&S used to simulate system performance in an operational environment
H	T	100	☑	Factory acceptance testing of laboratory system in laboratory setting
B	T	100	☑	Representative model / prototype tested in high-fidelity lab / simulated operational environment
B	T	100	☑	Realistic environment outside the lab, but not the eventual operating environment
B	T	100	☑	Laboratory system is high-fidelity functional prototype of operational system
B	T	100	☑	Engineering feasibility fully demonstrated

Comments:

H/SW Both	Ques Catgry	% Complete		TRL 7 (Check all that apply or use sliders)
H	T	100	☑	M&S used to simulate some unavailable elements of system, but these instances are rare
B	T	100	☑	Each system/software interface tested individually under stressed and anomolous conditions
B	T	100	☑	Operational environment, but not the eventual platform, e.g., test-bed aircraft
H	T		☐	Components are representative of production components
B	T	100	☑	Most functionality available for demonstration in simulated operational environment
B	T	100	☑	Operational/flight testing of laboratory system in representational environment
B	T	100	☑	Fully integrated prototype demonstrated in actual or simulated operational environment
B	T	100	☑	System prototype successfully tested in a field environment.

Inserted Values LAWS



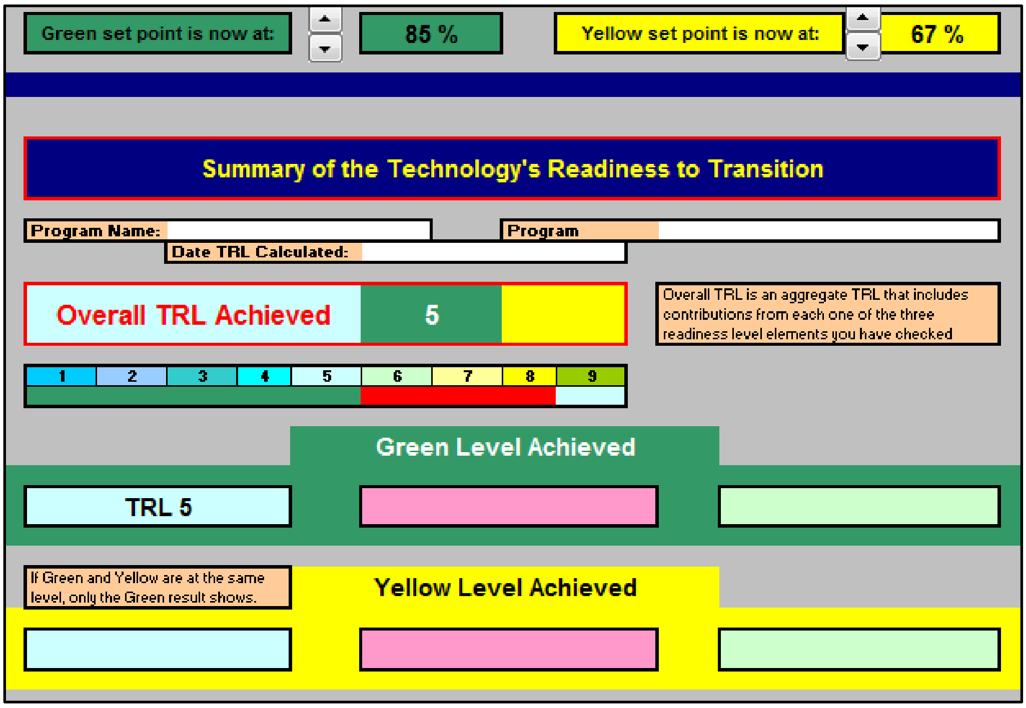
TRL Results LAWS

H/SW Both	Ques Catgry	% Complete	TRL 5 (Check all that apply or use sliders)
B	T	100	☑ Cross technology effects (if any) identified and established through analysis
B	T	100	☑ System interface requirements known
B	T	100	☑ Interfaces between components/subsystems are realistic (Breadboard with realistic interfaces
B	T	100	☑ High fidelity lab integration of system completed, ready for test in realistic/simulated environmen
H	T	100	☑ Fidelity of system mock-up improves from breadboard to brassboard
B	T	100	☑ Laboratory environment modified to approximate operational environment
B	T	100	☑ IPT develops requirements matrix with thresholds and objectives
B	T	100	☑ Physical work breakdown structure available

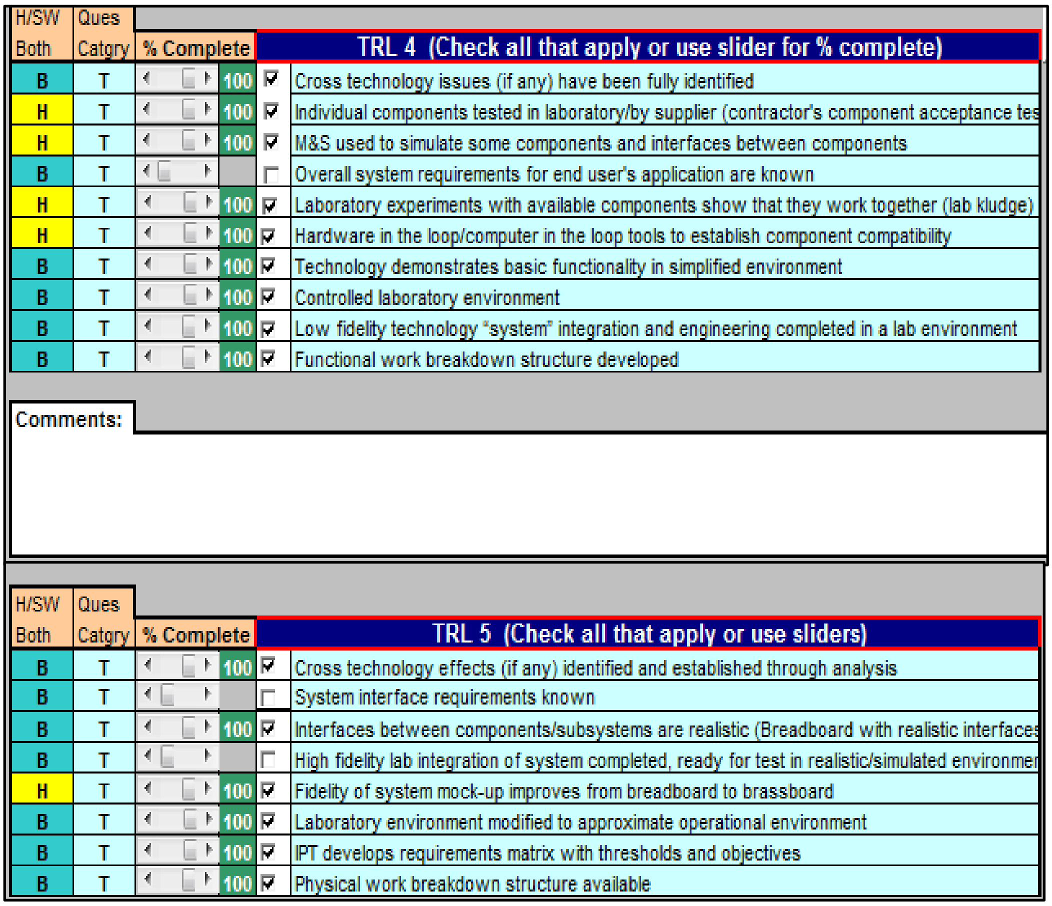
Comments:

H/SW Both	Ques Catgry	% Complete	TRL 6 (Check all that apply or use sliders)
B	T		☐ Cross technology issue measurement and performance characteristic validations completed
B	T		☐ Operating environment for eventual system known
B	T	100	☑ M&S used to simulate system performance in an operational environment
H	T		☐ Factory acceptance testing of laboratory system in laboratory setting
B	T	100	☑ Representative model / prototype tested in high-fidelity lab / simulated operational environment
B	T	100	☑ Realistic environment outside the lab, but not the eventual operating environment
B	T	100	☑ Laboratory system is high-fidelity functional prototype of operational system
B	T	100	☑ Engineering feasibility fully demonstrated

Inserted Values MLD



TRL Results MLD

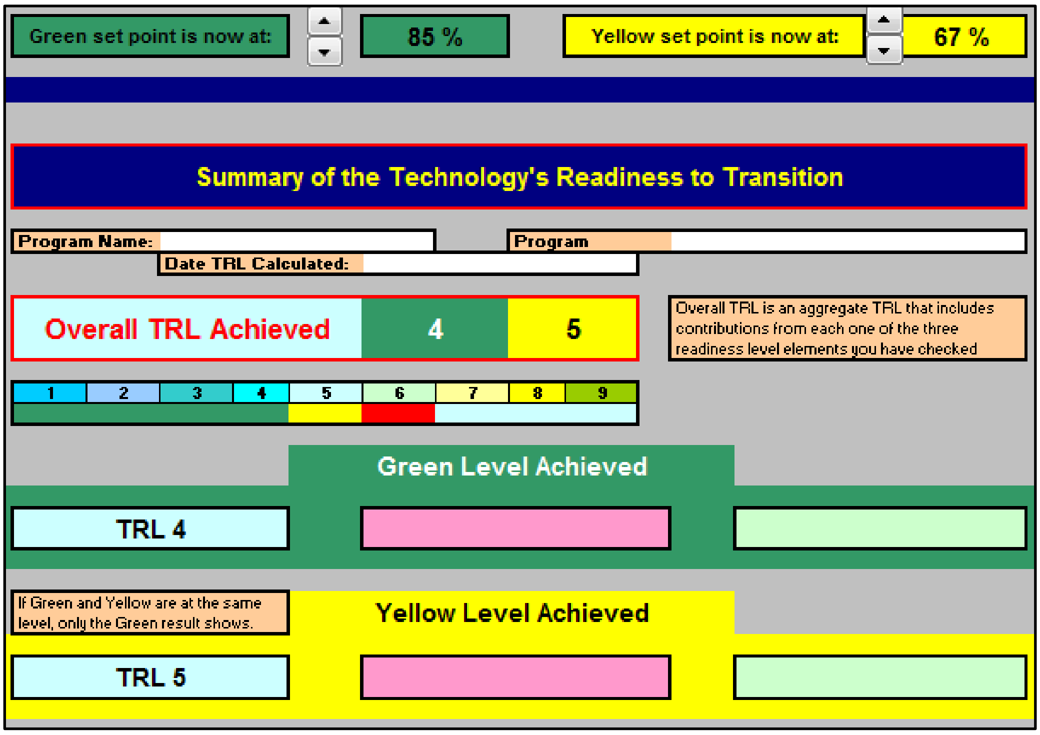


H/SW Both	Ques Catgry	% Complete		TRL 4 (Check all that apply or use slider for % complete)
B	T	100	☑	Cross technology issues (if any) have been fully identified
H	T	100	☑	Individual components tested in laboratory/by supplier (contractor's component acceptance tes
H	T	100	☑	M&S used to simulate some components and interfaces between components
B	T		☐	Overall system requirements for end user's application are known
H	T	100	☑	Laboratory experiments with available components show that they work together (lab kludge)
H	T	100	☑	Hardware in the loop/computer in the loop tools to establish component compatibility
B	T	100	☑	Technology demonstrates basic functionality in simplified environment
B	T	100	☑	Controlled laboratory environment
B	T	100	☑	Low fidelity technology "system" integration and engineering completed in a lab environment
B	T	100	☑	Functional work breakdown structure developed

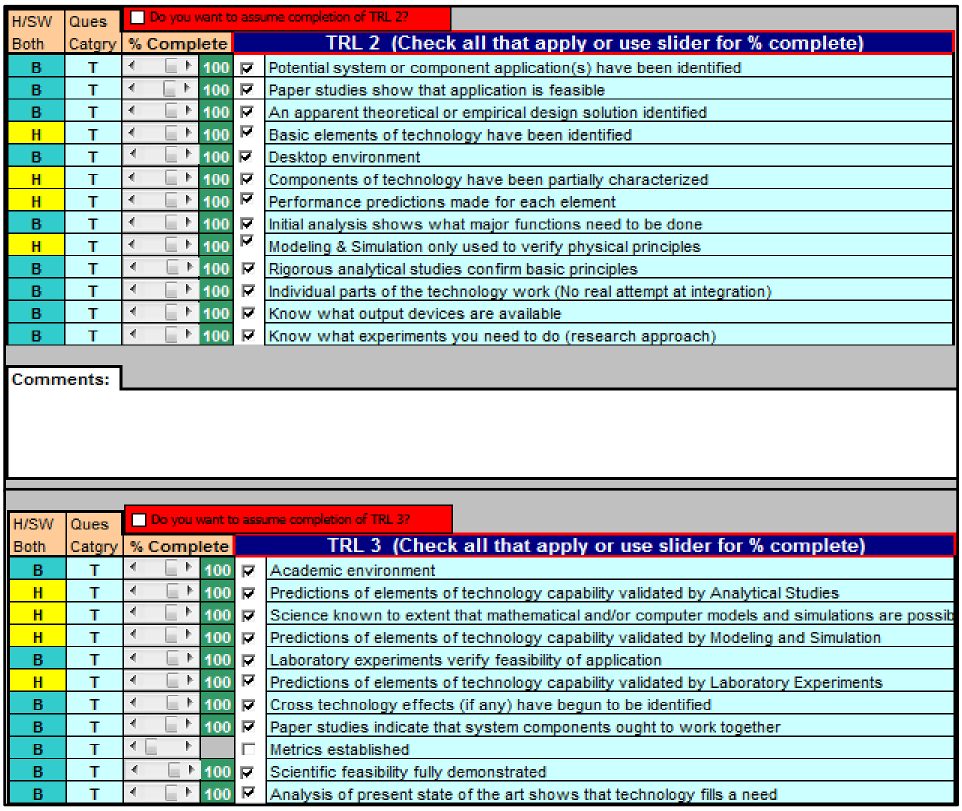
Comments:

H/SW Both	Ques Catgry	% Complete		TRL 5 (Check all that apply or use sliders)
B	T	100	☑	Cross technology effects (if any) identified and established through analysis
B	T		☐	System interface requirements known
B	T	100	☑	Interfaces between components/subsystems are realistic (Breadboard with realistic interfaces
B	T		☐	High fidelity lab integration of system completed, ready for test in realistic/simulated environmer
H	T	100	☑	Fidelity of system mock-up improves from breadboard to brassboard
B	T	100	☑	Laboratory environment modified to approximate operational environment
B	T	100	☑	IPT develops requirements matrix with thresholds and objectives
B	T	100	☑	Physical work breakdown structure available

Inserted Values MLD



TRL Results RELI

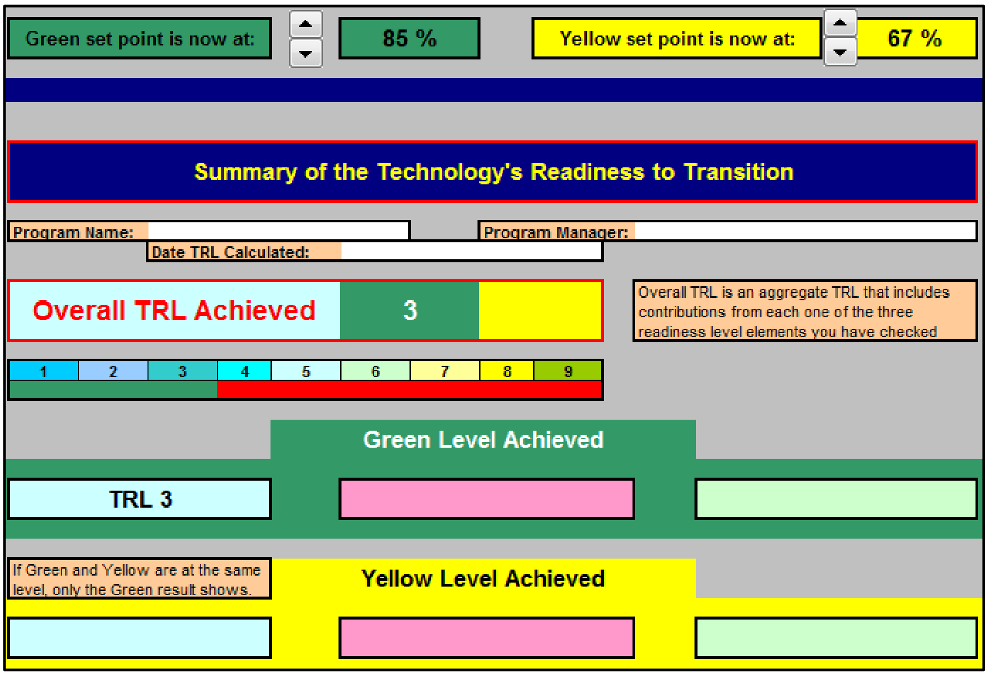


H/SW Both	Ques Catgry	% Complete	Do you want to assume completion of TRL 2? TRL 2 (Check all that apply or use slider for % complete)
B	T	100	Potential system or component application(s) have been identified
B	T	100	Paper studies show that application is feasible
B	T	100	An apparent theoretical or empirical design solution identified
H	T	100	Basic elements of technology have been identified
B	T	100	Desktop environment
H	T	100	Components of technology have been partially characterized
H	T	100	Performance predictions made for each element
B	T	100	Initial analysis shows what major functions need to be done
H	T	100	Modeling & Simulation only used to verify physical principles
B	T	100	Rigorous analytical studies confirm basic principles
B	T	100	Individual parts of the technology work (No real attempt at integration)
B	T	100	Know what output devices are available
B	T	100	Know what experiments you need to do (research approach)

Comments:

H/SW Both	Ques Catgry	% Complete	Do you want to assume completion of TRL 3? TRL 3 (Check all that apply or use slider for % complete)
B	T	100	Academic environment
H	T	100	Predictions of elements of technology capability validated by Analytical Studies
H	T	100	Science known to extent that mathematical and/or computer models and simulations are possib
H	T	100	Predictions of elements of technology capability validated by Modeling and Simulation
B	T	100	Laboratory experiments verify feasibility of application
H	T	100	Predictions of elements of technology capability validated by Laboratory Experiments
B	T	100	Cross technology effects (if any) have begun to be identified
B	T	100	Paper studies indicate that system components ought to work together
B	T		Metrics established
B	T	100	Scientific feasibility fully demonstrated
B	T	100	Analysis of present state of the art shows that technology fills a need

Inserted Values LDEW



TRL Results LDEW